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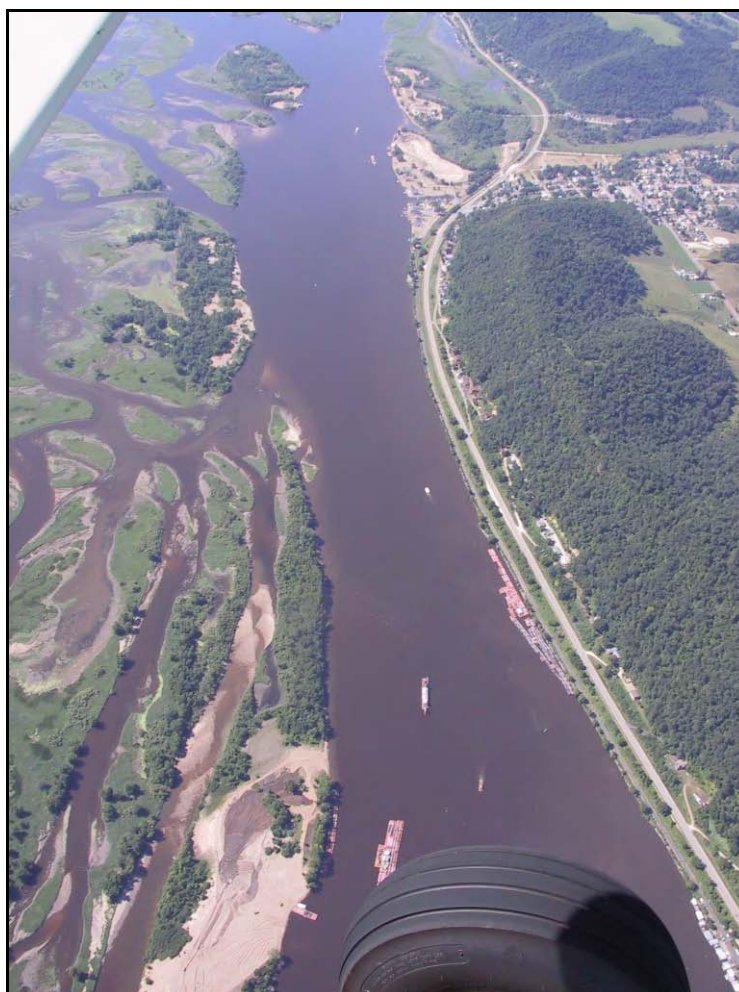
Monitoring Completed Navigation Projects Program

Effects of Pool Drawdown and Wing Dams (Pool 8), and Closure Dams (Pool 13), on Navigation Channel Sedimentation Processes, Upper Mississippi River

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ABSTRACT: Construction of navigation locks and dams on the upper Mississippi River about 60 years ago submerged wing dam training structures, thereby reducing their effectiveness and increasing secondary channel and floodplain conveyance. The U.S. Army Engineer District, St. Paul, executed a drawdown of Pool 8 (upstream of Lock and Dam No. 8) near La Crosse, WI, during the summers of 2001 and 2002. Water levels were allowed to drop below normal minimum values to expose mud flats, promote seed germination, and benefit fish and wildlife. By lowering water levels during a drawdown, wing dam training structures submergence and floodplain conveyance will be decreased, and flow patterns around the training structures will be altered. This could result in sediment mobilization and scour in the navigation channel.

During the spring of 2001, three closure dams were constructed in Pool 13 (upstream of Lock and Dam No.13) by the U.S. Army Engineer District, Rock Island, near Savanna, IL. These closure dams are actually submerged weirs that should allow water to continue to flow into the backwater areas of the islands of Pool 13, but at reduced rates. At issue is whether the main channel might require reduced dredging in future years as a result of the construction of the closure dams and, also, whether the backwaters of the eastern side of the islands will fill with sediment.

A new and expedient methodology for the computation of bed-load transport (Integrated Section Surface Difference Over Time (ISSDOT)) was developed using multi-beam bathymetric data. The total river bed volume change with time, when multiplied by the density of the water/sediment mixture, yields a mass transport rate. Results of ISSDOT computations for Pool 8, and other analyses (sediment budget and geographic information system (GIS) analyses, and transport function analysis) of the same river region, confirm that: (a) the observed drawdown did indeed have the effect of increasing sediment mobilization within the study reach, (b) the original wing dam structures as designed, and in conjunction with a drawdown, positively influence sediment movement in the reach, and (c) it will be possible to project sediment movement before, during, and after such drawdown events. By utilizing ISSDOT technology and other river management information gleaned from this monitoring study, river managers can more efficiently plan their dredging requirements for events such as the Pool 8 drawdown.

For the region of interest at Pool 13, in the main channel, two areas showed short-term occurrences of scour and then re-deposition that was measurable and statistically significant. However, over the entire monitoring period of November 2001 to July 2004, the net result showed no discernable change in the main channel bathymetry with regard to average depths in these two areas. A third area of the main channel showed the same scour and then deposition trend as the other two areas for the same time periods. However, over the entire monitoring period, the net result was a discernable scour trend in the main channel. For the back channel, one area showed a net deposition trend of nearly 0.15 m (0.5 ft) in that area between June 2002 and July 2004. In another area of the back channel, all measurements showed a net deposition trend with the maximum being about 0.34 m (1.1 ft) over the entire survey period of 32 months. The net deposition in the back channel is statistically significant. As in the main channel, whether the deposition in the back channel will continue cannot be determined from the present data.

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Preface

Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02832	cubic meters per second
cubic yards	0.76455285	cubic meters
feet	0.3048	meters
miles	1.6093	kilometers
pounds (force) per second per foot	1.483051	kilograms (force) per second per meter
pounds (force) per square foot	4.88243	kilograms (force) per square meter
tons	907.1847	kilograms
tons	0.9071847	metric tons
tons per day	907.1847	kilograms per day
tons per day	0.9071847	metric tons per day
tons per year	907.1847	kilograms per year

1   Introduction

Monitoring Completed Navigation Projects Program

The goal of the Monitoring Completed Navigation Projects (MCNP) program [formerly the Monitoring Completed Coastal Projects (MCCP) program] is the advancement of coastal and hydraulic engineering technology. The program is designed to determine how well projects are accomplishing their purposes and how well they are resisting attacks by their physical environment. These determinations, combined with concepts and understanding already available, will lead to (a) the creation of more accurate and economical engineering solutions to coastal and hydraulic problems, (b) stronger and improved design criteria and methodology, (c) improved construction practices and cost effectiveness, and (d) improved operation and maintenance techniques. Additionally, the monitoring program will identify where current technology is inadequate or where additional research is required.

To develop direction for the program, the U.S. Army Corps of Engineers (USACE) established an ad hoc committee of engineers and scientists. The committee formulated the objectives of the program, developed its operation philosophy, recommended funding levels, and established criteria and procedures for project selection. A significant result of their efforts was a prioritized listing of problem areas to be addressed. This is essentially a listing of the areas of interest of the program.

Corps offices are invited to nominate projects for inclusion in the monitoring program as funds become available. The MCNP program is governed by Engineer Regulation 1110-2-8151 [Headquarters, U.S. Army Corps of Engineers (HQUSACE) 1997]. A selection committee reviews and prioritizes the nominated projects based on criteria established in the regulation. The prioritized list is reviewed by the Program Monitors at HQUSACE. The final selection is based on this prioritized list, national priorities, and the availability of funding.

The overall monitoring program is under the management of the Coastal and Hydraulics Laboratory (CHL), U.S. Army Engineer Research and Development Center (ERDC), with guidance from HQUSACE. An individual monitoring project is a cooperative effort between the submitting District and/or Division office and CHL. The development of monitoring plans and conduct of data collection and analyses depend on the combined resources of CHL and the District and/or Division.

Background

Channel training structures (wing dams and closure dams) that are currently in place on the upper Mississippi River were constructed more than 100 years ago to increase flow in the navigation channel and cause scour to occur, thus resulting in a deeper channel. Initially, these structures accomplished this goal, as evidenced by the islands and sandbars that formed around them. The construction of the locks and dams 60 years ago submerged the training structures, reducing their effectiveness and increasing secondary channel and floodplain conveyance. Both training structure submergence and floodplain conveyance are functions of longitudinal position within the pool, generally increasing from the upstream to the downstream end of the pool.

Pool 8

In cooperation with the U.S. Fish and Wildlife Service (USFWS) and the Departments of Natural Resources from Minnesota and Wisconsin, the U.S. Army Engineer District, St. Paul, executed a drawdown of Pool 8 (Figure 1) (upstream of Lock and Dam No. 8) on the upper Mississippi River near La Crosse, WI, during the summers of 2001 and 2002. Water levels were allowed to drop below normal minimum values at Lock and Dam No. 8 to expose mud flats, promote seed germination, and benefit fish and wildlife. The pool is normally drawn down to elevation (el) 192.0 m (630.0 ft) National Geodetic Vertical
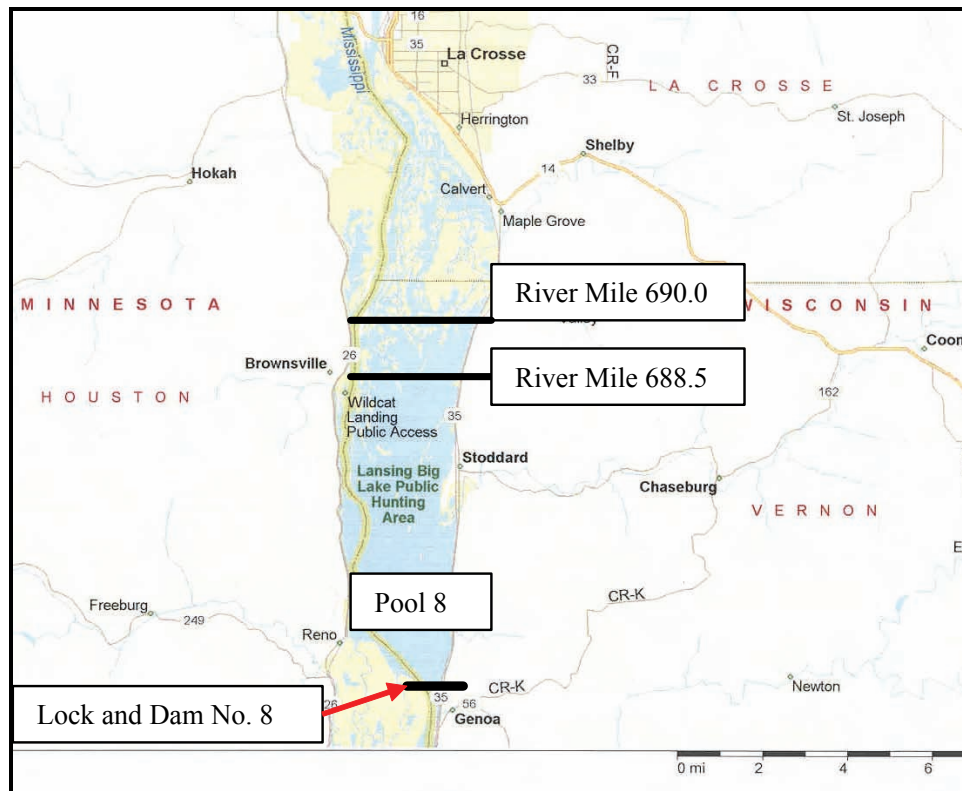
Figure 1. Pool 8, upstream of Lock and Dam No. 8, upper Mississippi River near LaCrosse, WI

Datum (NGVD) at Lock and Dam No. 8. In 2001, the drawdown was to el 191.6 m (628.5 ft) and thus was 0.46 m (1.5) ft lower than normal. In Pool 8, most of the dredging is done in the middle reach of the pool between Mississippi River Mile 690.0 and River Mile 688.5. This is a reach where the combination of training structure submergence, high floodplain conveyance, and coarse sediment availability results in sediment deposition. By lowering water levels during a drawdown, training structure submergence and floodplain conveyance will be decreased, and flow patterns between and around the training structures will be altered. This could result in sediment mobilization and scour in the navigation channel.

Pool 13

During the spring of 2001, three closure dams were constructed in Pool 13 (Figure 2) (upstream of Lock and Dam No. 13) near Savanna, IL. The first is immediately north of Island No. 266, the second is immediately north of Sweeney Island, and the third is immediately south of Sweeney Island. These closure dams are actually submerged weirs that should allow water to continue to flow into the backwater areas of these two islands in Pool 13, but at reduced quantities. At issue is whether the main channel might require less dredging in future years as a result of the construction of the closure dams and also whether the backwaters of the eastern side of the islands will fill with sediment. The river reach of interest lies between Mississippi River Mile 539.5 and River Mile 538.5 (including the islands and backwater areas).
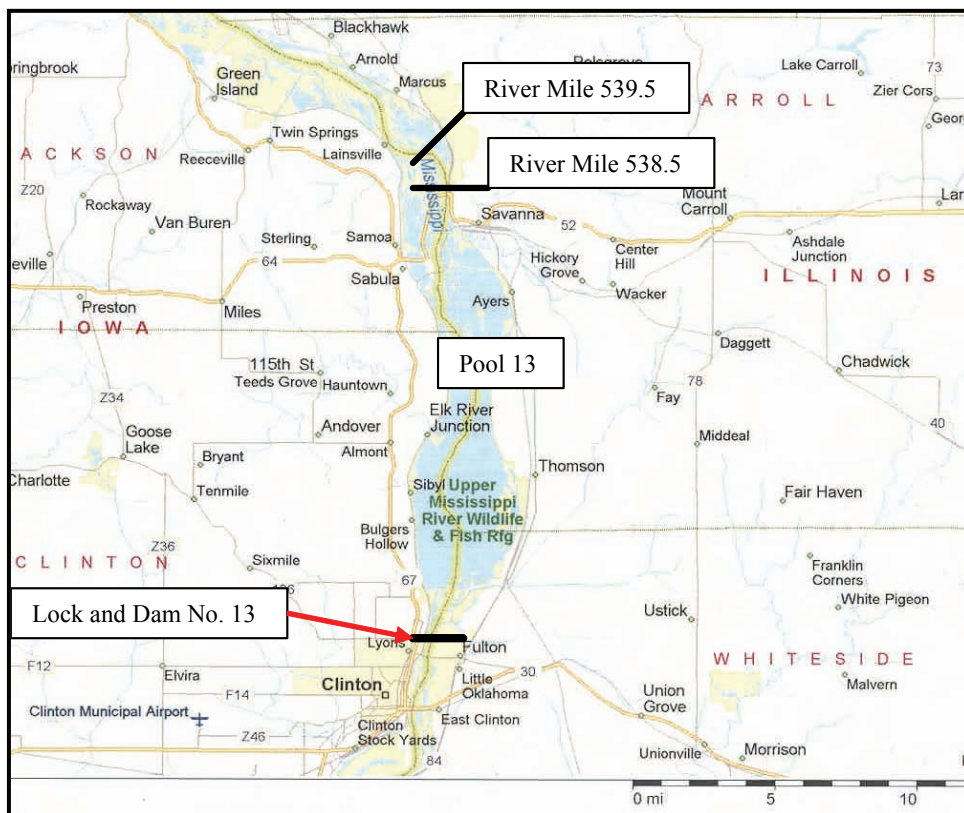
Figure 2.   Pool 13, upstream of Lock and Dam No. 13, near Savanna, IL

Purposes of the Study

Pool 8

It was unknown how the flow and sediment movement in the vicinity of the wing dams in Pool 8 might change during a drawdown. Monitoring would be required to quantify the effects of this water level management technique on hydrodynamic and sediment transport processes. Monitoring would allow navigation channel managers to better assess potential costs and benefits of future water level drawdowns. By measuring hydraulic and sediment parameters before, during, and after the drawdown, comparisons can be made to determine if sediment movement increased.

There are 40 wing dam structures in the reach of interest. Many of these are now integral parts of islands, bars, and/or banks. This monitoring was directed toward the structures that still protrude into the channel, and their influence on flow and sedimentation patterns during and after drawdown. If these protruding structures, or any combination of these existing and future new protruding structures, might work together with a drawdown to move sediment through the depositional reach, then an optimum situation could be achieved in terms of wildlife and sediment management. However, there exists the possibility of negative sedimentation impacts, as sediments may deposit in other areas of Pool 8.

St. Paul District is interested in numerical modeling of new structure configurations that, together with the old structures, might enhance sediment movement through the reach during the drawdown and might provide additional fish habitat during normal pool operations. The enhancement of fish and aquatic habitat around training structures has received widespread national attention in recent years. Most aquatic biologists agree that two of the most important fish habitat considerations are water depth and velocity around structures. Acquiring this type of information from a numerical code requires the capability of resolving vertical accelerations in the near flow fields. Two-dimensional numerical codes cannot do this adequately, so quantifying the location and depth of scour and deposition in the immediate vicinity of training structures has not been possible.

New, non-hydrostatic numerical codes are becoming available that can be used to assess the hydraulics of the near flow fields. These codes will be adapted and modified as necessary to simulate the near flow fields in Pool 8. Monitoring data will be analyzed as it becomes available, giving the data a secondary benefit as a check of the performance of these new numerical codes. The codes will be adapted to simulate new structural configurations the District may desire to evaluate in light of the knowledge gained from the monitoring effort. Thus, a predictive capability will be developed.

Pool 13

The U.S. Army Engineer District, Rock Island, has performed a substantial amount of historical and recent dredging in the Mississippi River reach of interest to maintain the authorized navigation channel depth. The channel thalweg near

Savanna, IL, lies along the outside of a sharp-radius bend through this area. A depositional bar forms along the inside of the bend, restricting the available width through the reach.

The closure dams were designed and constructed to reduce the amount of flow through the back channels behind the island and thereby increase the velocities in the main channel to reduce sediment deposition and to encourage a more reliable navigation channel that would require less maintenance dredging. The upper two closure dams were built to 1.5 m (5 ft) below the flat pool, and the lower dam is emergent. These closure dams are actually submerged weirs that should allow water to continue to flow into the backwater areas of these two islands.

Early in the planning stages of the project, a concern was raised that the reduced flow in the back channel could induce sedimentation behind the islands and result in a loss of valuable over-wintering habitat for fish. To address these concerns, numerical modeling, flow visualization, and micro-modeling were performed by the U.S. Army Engineer District, Rock Island, and the U.S. Army Engineer District, St. Louis, to evaluate the sediment transport and hydrodynamic response trends that could be expected to occur from construction of the closure dams (Kirkeeng et al. 1998). The results of the model efforts indicated that the construction of the closure dams would not result in significant sedimentation in the back channel areas of Island No. 266 and Sweeney Island. Monitoring would be conducted to determine if the closure dams were performing as desired and to provide guidance about the development of other closure dams in future projects.

Hypotheses

Specific hypotheses were used to develop the monitoring plan and were tested through monitoring of Pools 8 and 13. In Pool 8, a pool drawdown was conducted to evaluate the effects on sediment movement between and around the protruding wing dams of that study reach. In Pool 13, closure dams were constructed, and it is desirable to know the effects of these closure dams on sediment movement through that study reach. While the causes of sedimentation changes are distinctly different for the two pools, knowledge of how the closure dams affect sediment movement in the navigation channels of both study reaches is essential. Hence, the same hypothesis and logical reasoning are applicable to both situations.

It is important to determine whether the closure dams, as well as the existing wing dams in combination with drawdown, will increase velocities enough to increase sediment movement through the deposition reach. Measurements of hydraulic and sediment parameters before, during, and after the drawdown allow comparisons to determine if sediment movement increased.

Two methodologies were used to determine if net sediment movement occurred. The first method used reach bathymetric data collected by the Districts. These data are available for the entire main channel for the years 1996 through 2001. Surveys were made before, during, and after drawdown in Pool 8 and before, during, and after construction of the closure dams in Pool 13. Analysis of

these and previous additional data collected by the Districts were used to reveal whether net sediment movement occurred. These data were also used to try to determine if the net movement was a result of the drawdown and/or structure interaction, or if such sediment movement would have occurred under normal pool operations.

The second method to determine if sediment movement increased was to measure the bed material load and suspended sediment fluxes at selected structures in the reach and at the inflow and outflow sections of the reach. This was also done before, during, and after the drawdown. Analysis of this data provided evidence as to whether sediment movement increased in the reach because of the drawdown.

The measurement of suspended sediment fluxes is well established in theory and practice. The standard P-61 sampling technique was used. The actual prototype measurement of bed material load in sand-bed streams and rivers is not physically possible. The Helley-Smith bed material load sampler has been shown to be somewhat effective in small streams and for gravel and cobble, but not in sand-bed streams. The methodology for this monitoring used the newest technologies available. High-resolution multi-beam acoustic profilers were used to measure sand wave movements by means of an Integrated Section Surface Difference Over Time (ISSDOT) technique. A control volume approach was utilized, mapping the horizontal migrations and vertical changes of the sand waves as they traversed the control volume in a given time. Additionally, acoustic doppler profilers were used at the same locations to map velocity profiles. These were useful in determining the vertical velocity profile to within several feet of the river bottom. Extrapolations of this profile were made, making it possible to determine the critical shear stress for use in bed-load function calculations. Transport rates and bed changes in the vicinity of the structures were then computed and compared for conditions before, during, and after the drawdown.

Monitoring Plan

At the initiation of this study, it was understood that a methodology for quantifying bed-load transport in large rivers would need to be developed. An intensive literature review and collaboration with other river engineers and scientists in the United States and Europe indicated that no adequate, universally accepted bed-load measurement technique existed for large sand-bed rivers. The use of high-resolution bathymetric data to determine bed-load transport was conceived, and a new method was developed that uses such data collected over the same bottom terrain at know differences in time. This new methodology is the Integrated Section Surface Difference Over Time (ISSDOT) technique. The integration is a summation of incremental transport values across the channel cross section (not an integration over the surface of each computational element). ISSDOT was calibrated, verified, and perfected using field data obtained during periodic river surveys during dates show in Table 1. Hydraulic, sediment, and bathymetric data were obtained during each field survey event.

Table 1		
Field Surveys, Pool 8 and Pool 13		
Location	**Survey No.**	**Date of Survey**
Pool 8	1	June 2001
Pool 8	2	July 2001
Pool 8	3	November 2001
Pool 8	4	June 2002
Pool 13	1	November 2001
Pool 13	2	June 2002
Pool 13	3	September 2003
Pool 13	4	July 2004

Pool 8

It was necessary to obtain specific bathymetric, hydraulic, and sediment data to determine the wing dams/drawdown effects on hydraulic parameters and sediment movement. These data included the following:

a. Data requirements to determine bathymetry changes:

(1) Prior bathymetric surveys in the study reach (conducted by the District), and

(2) Bathymetric surveys obtained before, during, and after drawdown in the same reach (also conducted by the District).

b. Data requirements to determine hydraulic and sediment transport changes:

(1) Velocity fields of the entire cross sections upstream, over, and downstream of the most intrusive structures and at the inflow (River Mile 690.0) and outflow (River Mile 688.5) boundaries of the study reach (five cross sections) (obtained by ERDC),

(2) Static velocity profiles at several locations along the structures and their cross sections and at the inflow (River Mile 690.0) and outflow (River Mile 688.5) boundaries of the study reach (obtained by ERDC),

(3) Suspended sediment samples taken concurrently and at the same locations as the static velocity profiles (obtained by ERDC),

(4) Bed-material load measurements around the most intrusive structures and at the inflow and outflow boundaries of the study reach by high-resolution multi-beam surveys at these cross sections over space and time scales sufficient to capture any bedform movements, depending on the existence of dunes in this reach (developed by ERDC), and

(5) Bed material samples (to obtain bed gradation curves) around the most intrusive structures and at the inflow and outflow boundaries of the study reach (obtained by the District).

Pool 13

It was necessary to obtain specific bathymetric, hydraulic, and sediment data to determine the closure dams' effects on hydraulic parameters and sediment movement. These data included the following:

    a. Data requirements to determine bathymetry changes:

        (1) A multi-beam survey of the main channel between River Mile 539.5 and River Mile 538.5 (obtained by ERDC), and

        (2) A multi-beam survey of the backwater channels east of the islands (also obtained by ERDC).

    b. Data requirements to determine hydraulic and sediment transport changes:

        (1) Velocity fields of the entire cross sections upstream and downstream of the closure dams and at the inflow (River Mile 539.5) and outflow (River Mile 538.5) boundaries of the study reach (six cross sections) (obtained by ERDC),

        (2) Static velocity profiles at several locations along the closure structures and at the inflow (River Mile 539.5) and outflow (River Mile 538.5) boundaries of the study reach (obtained by ERDC),

        (3) Suspended sediment samples taken concurrently and at the same locations as the static velocity profiles (obtained by EDC),

        (4) Bed-material load measurements at River Mile 539.0 by high-resolution multi-beam surveys at this cross section over space and time scales sufficient to capture any bedform movements depending on the existence of dunes in this reach (developed by ERDC), and

        (5) Bed material samples (to obtain bed gradation curves) around the closure dams and at the inflow and outflow boundaries of the study reach (obtained by the District).

2 Quantification of Bed-Load Transport Using ISSDOT and Traditional Methods

The need for quantifying bed-load transport is universal in riverine and coastal processes. In the past, many analytical and mechanical methods have been devised to try to quantify bed-load transport on large sand-bed rivers. Most methods have been only marginally successful. In this monitoring study, the ability to quantify the bed load accurately was essential in determining whether river training structures in combination with a drawdown of the navigation pool had a significant effect on net sediment movement through a given reach of river. Accurate measurements would resolve whether the altering of the pool stage and flow schedules might also be used as a sediment management tool. A new and expedient methodology for the computation of bed-load transport (ISSDOT) was developed using multi-beam bathymetric data (Abraham and Pratt 2002).

Measurement Method

Two methods for utilizing multi-beam survey technology were initially conceived. One method was based on the celerity of the traveling sand waves. The other was based on the difference of section surfaces. After careful deliberation, the section surface difference method, ISSDOT, was developed and implemented. This method processes multi-beam data and quantifies a bed-load transport rate for a given river cross section. This is accomplished by taking at least two sets of bathymetric data, at different times, for the same location. The two data sets are interpolated to a spatial grid, and a difference plot is produced. Incremental volumes are calculated and summed over the entire cross section. The total volume change with time, when multiplied by the density of the water/sediment mixture, yields a mass transport rate. ISSDOT has produced results similar to those of other standard analytical methods.

Bed-Load Transport Definitions

For the purposes of defining the limitations and applicability of the ISSDOT method, the definitions by Einstein (1950), Colby (1963), Bagnold (1966), and van Rijn (1984) for bed load were considered. Intuitively, all of these seem to define bed load in similar terms. That is, the material of which the bed is

composed is transported by rolling and sliding, and by *skipping* or *hopping* or *jumping*. These last three terms seem to be used interchangeably in a loose sense by many authors and are probably what most authors refer to when they speak of saltating particles. However, important distinctions should be noted. Einstein defines jumping as leaps of no more than 100 grain diameters long. Bagnold calls bed load the movement of particles whose successive contacts with the bed are limited by the effects of gravity. That means that the particles do not go into suspension. Suspended bed-load material is then defined as that in which the excess weight of the particles is supported by the upward impulses of turbulence. van Rijn chooses a similar definition.

For this investigation, a definition similar to those of Bagnold and van Rijn was considered most appropriate. Bed load, for the purposes of the ISSDOT method, is defined as sediment that is transported in a stream by rolling, sliding, or saltating along the bed while remaining very close to the bed. For calculations of bed load moving in dunes or sand waves, the following necessary condition should be added: If particles temporarily go into suspension for distances greater than the length of the smallest of the dunes, then these particles should be considered as suspended. Otherwise, they can be considered to be bed load.

Constraints

The movement of a sand wave occurs when the upstream surface of the crest is scoured and this material is then deposited on the downstream face of the wave. With this mechanism of movement, limitations exist for the computational procedure to provide meaningful results. First, as noted in the definitions, the particles that move the sand wave cannot completely jump over an entire wave. Second, the speed of the wave must be such that the length that it travels in a given time must not be greater than the length of the computational grid. Third, it is assumed that, within a given control volume, the bed-load transport rate is at a steady state. Fourth, with regards to sand wave regime theory, the flow cannot be such that the dune bed will transition into a plane bed or anti-dunes.

Additional constraints are related to the collected data. For either the ISSDOT or wave celerity methods to provide valid results, the sequential "snapshots" of the bathymetric features must be accurate in space and time and measured to the same datum. All of these constraints have been recognized and fully evaluated in the development of the ISSDOT method.

Prototype Field Site

The location of the monitoring site and specific study area used to develop the ISSDOT measurement technique was Pool 8 on the upper Mississippi River, just south of LaCrosse, WI. A schematic of the study area in Pool 8 is shown in Figure 3. The entire bathymetry of the reach was mapped during the first survey trip in June 2001. In subsequent survey trips, only the area between River Mile 688.7 and River Mile 689.2 was mapped. Sediment transport and the effects of

wing dam Structures 54 and 55 (Figure 3) were monitored and evaluated in this region. Figures 4 and 5 show different views of Pool 8 and the study area.
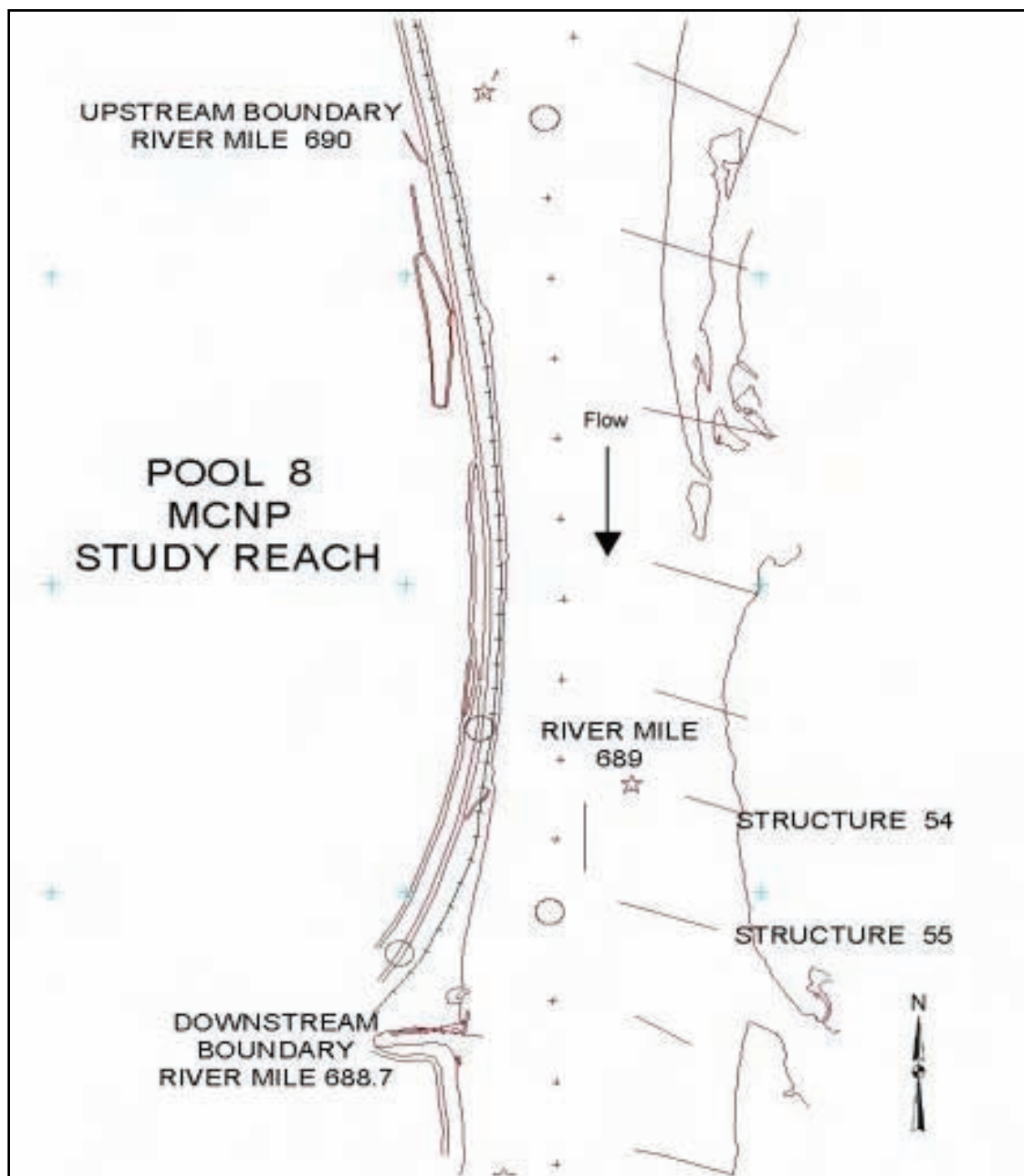
Figure 3. Schematic of Pool 8 study area

Figure 4. Lower portion of Pool 8 looking downstream (south), with Brownsville, MI, and the study area at the right and center of the photograph, respectively

Figure 5. Entire length of the Pool 8 study area, with Brownsville, MI, at the top right of the photograph

Data Collection

The field data collection survey boat is shown in Figures 6 and 7. Multi-beam bottom profiling, acoustic doppler current profiler (ADCP) velocity measurements, and sediment data are all collected from this platform. The boat is equipped with a global positioning system (GPS) that fully compensates for pitch, heave, and roll.

Figure 6.   Survey boat for acquiring hydrographic, sediment, and bathymetric data

Figure 8 shows some results of the data collected in the study area. The results of the survey trip 1 bathymetric survey are shown in the yellow-green-blue background. The bathymetric features are clearly visible. Sediment samples and static velocity measurements were taken at the numbered locations. Additional swaths of bathymetric data were acquired at four times on the same day; these data were obtained from the brown sections at points 7, 6, 5, and 2.

The elevation data represented in Figure 8 are exceedingly dense. These data were used in the ISSDOT methodology for quantifying bed-load transport. For example, Figure 9 shows a longitudinal profile through the north–south swath at four times. This plot shows the longitudinal profile of the four "snapshots" represented by the four swaths. Each color, therefore, represents the same wave at different points in time. From this profile the distance that the wave front traveled from time 1 to time 2, etc., can be determined, so the wave celerity is known. Also, the basic wave shape and dimensions can be quantified.

Figure 7. Survey boat on-board computers, which provide boat location and monitor all data collection activities for multi-beam and ADCP instrumentation

Computational Methodology

When it was determined that the swaths had captured sufficient bed wave movement during their time spans (2.3–4.8 hr), the ISSDOT method was applied. The coordinates of a rectangle common to all four swaths were identified. Then a computational grid consisting of 0.3-m (1-ft) squares was developed. The data from each of the four swaths (snapshots) were interpolated to four separate grids. These grids with their associated bathymetric elevations represented the exact same surface at four points in time. Any one grid can be subtracted from another to produce a difference plot. The difference for any square foot between surface 1 and surface 2, for example, represents the change in volume over time for that area. Both deposition into and scour from any element are considered as positive transport. Summing all the incremental changes in volume across the section produces the net change in volume over time for the section. This value is then multiplied by the density of the sediment/water mixture to yield a bed-load transport rate.

A careful review of the scientific literature reveals that, although simple in principle, this concept has not been used previously by any other researcher. There are at least two good reasons. First, the literature seems to focus on the longitudinal profiles of the waves. Thus, in quantifying these characteristics of the waves, different methods of bed-load calculations are carried out to determine the bed-load transport rate of a given wave. There have been many excellent studies performed in this manner, such as those of Simons, Richardson and Nordin (1965), Willis and Kennedy (1977), and Mahmood (1985). Kennedy and Odgaard (1991) present an excellent review of riverine sand dune literature.
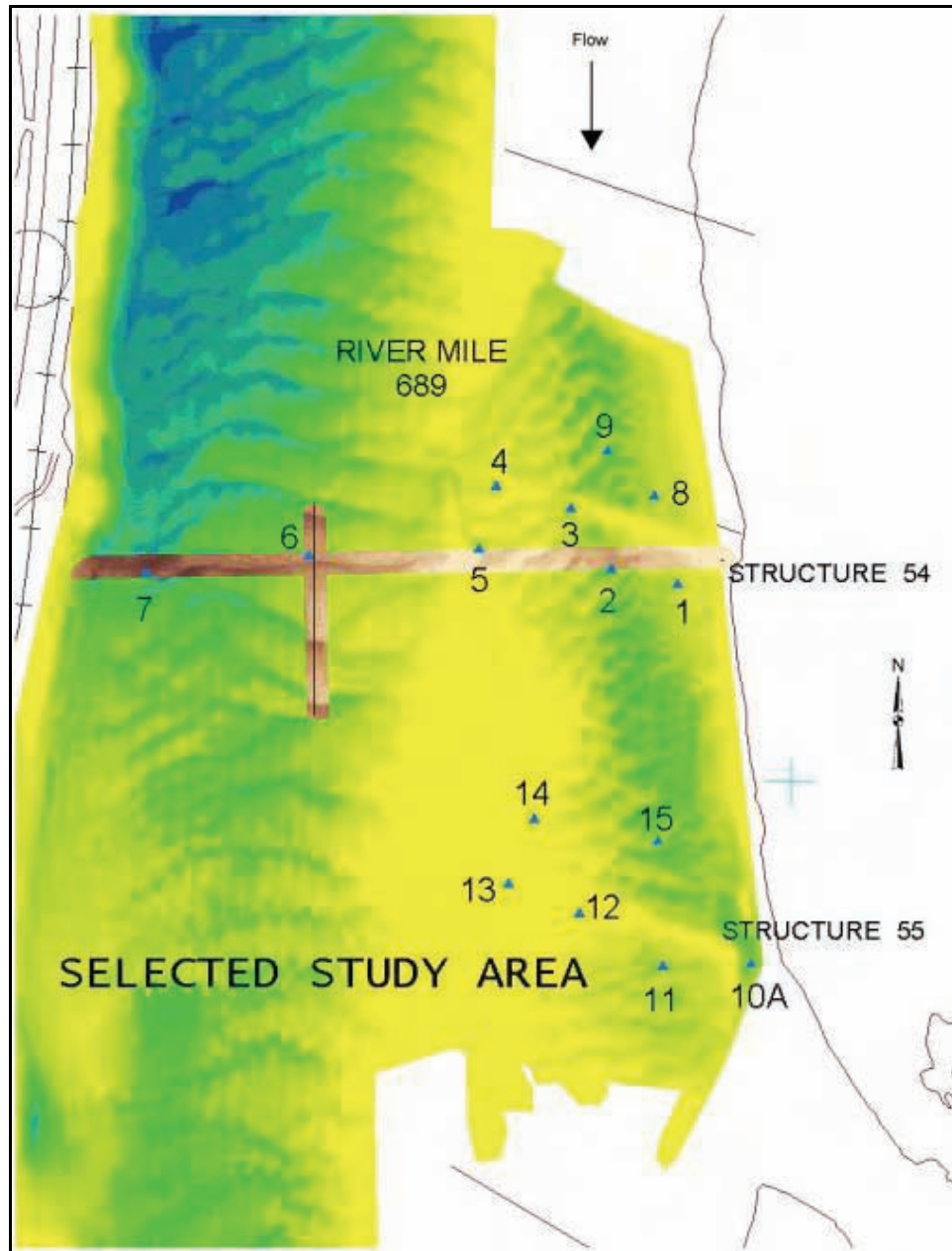
Figure 8.   Bathymetry of Pool 8 selected study area

Other than empirical methods based on sediment and hydraulic characteristics, they all appear to focus on two-dimensional wave shape and celerity, or on some type of statistical analysis of two-dimensional dune profiles. A bed-load transport rate calculated in either of these two manners is applicable to only the two-dimensional wave under consideration. In large sand-bed rivers, generally the sand waves are anything but consistent in size and celerity, both longitudinally and laterally. Inevitably, therefore, many assumptions and extrapolations must be made in order to determine anything meaningful regarding the bed-load transport rate of the entire section. This is the main difference between the ISSDOT method and previous traditional methods of computation. ISSDOT was
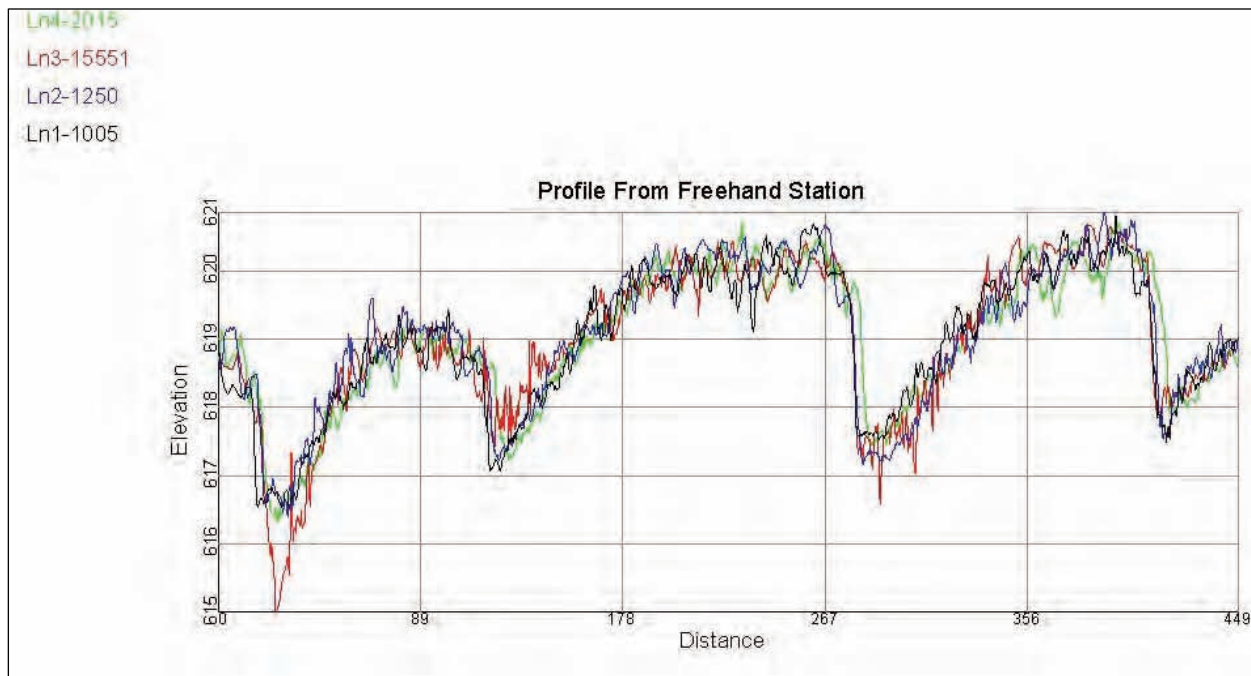
Figure 9.   Sample of four longitudinal bed profiles in the Pool 8 study area

conceived as a control volume method to preclude the necessity of dealing with spatially varying wave celerities and/or dune profile statistics.

A second reason that the ISSDOT computational methodology has not been previously considered practical relates to changing technology. The quality and quantity of multi-beam intensely detailed bathymetric data required to make this method work were not available until recently.

Results

Since it is physically impossible to measure total bed-load transport rates in large sand-bed rivers, other verification techniques must be used to determine the accuracy of the ISSDOT method for computing bed-load transport. There are at least two techniques for determining the accuracy of the ISSDOT method. The first is to compare ISSDOT results with mechanically measured data values on the same or similar rivers, taken at discrete locations and integrated across the entire river width. A second technique is to compare ISSDOT results with accepted analytic transport functions. Both techniques were applied.

For Pool 8 using the multi-beam data and the ISSDOT method, a value of 0.0041 kg/sec/m (0.003 lb/sec/ft) of width was calculated. This is equivalent to about 148,780 kg/day (164 tons/day), or about 149 metric tons/day.

For the first technique, data taken on the Nile River in Egypt in 1991 (van Rijn and Gaweesh 1994) using the Delft-Nile Sampler were used as a comparison for mechanically collected data. These data were used because the hydraulic and sediment characteristics of the Nile River in the vicinity of the measurements were very close to those of Pool 8 on the upper Mississippi River. The average

bed-load transport was determined by averaging the data for six measurement sites on the Nile (van Rijn and Gaweesh 1994). The result was 0.0175 kg/sec/m (0.0118 lb/sec/ft) of width. This is equivalent to about 635.030 kg/day (700 tons/day), or about 635 metric tons/day. Thus, the measured value for the Nile River is about four times the ISSDOT computed value for Pool 8 on the upper Mississippi River.

For the second technique, three analytical transport functions were selected and run using average channel parameters and the sediment characteristics of Pool 8. These functions were Einstein's bed-load function, Toffaleti's function (Toffaleti 1968), and van Rijn's function. These three transport functions computed 2,250,725 kg/day (2,481 tons/day), 312,070 kg/day (344 tons/day), and 1,684,640 kg/day (1,857 tons/day), respectively (2,255; 312; and 1,688 metric tons/day, respectively) of the bed-load portion of the bed-material load. The Toffaleti procedure produced results that were slightly more than twice the value computed using the ISSDOT method. The other two methods were substantially higher.

The ISSDOT methodology for determining bed-load transport slightly underpredicts transport when compared to both the mechanical bed sampling method and the analytical methods. The reason for this underprediction is related to the time-step interval between successive bathymetric measurements. It was apparent that future survey trips would need to take the "snapshot" surveys at shorter and more regularly spaced time intervals. Ultimately, large-scale proof-of-concept laboratory flume studies should be conducted.

3 Effects of Drawdown and Wing Dam Structures on Bed-Load Transport in Pool 8 Navigation Channel

In the summer of 2001, the St. Paul District executed a drawdown of Pool 8 on the upper Mississippi River to el 191.6 m (628.5 ft) [0.46 m (1.5 ft) lower than normal]. Wing dam training structure submergence and floodplain conveyance were decreased. Flow patterns between and around the training structures were altered. It was desired to understand how these flow pattern changes might affect sediment mobilization and scour in the navigation channel. Monitoring was conducted in accordance with the previously described monitoring plan.

Three methodologies were used to determine if net sediment movement occurred in the study reach of interest (Figure 10). (1) The first method used detailed multi-beam bathymetric data taken in the vicinity of River Mile 689.2. These data were analyzed using ISSDOT. (2) The second method used long-term data previously collected by the St. Paul District. These data included suspended

Figure 10. Aerial view of the study reach of interest of Pool 8, upper Mississippi River

sediment measurements and bathymetric data and were analyzed in the form of a sediment budget and through GIS manipulation. (3) The third method used measured sediment and hydraulic data that were analyzed using sediment transport functions.

ISSDOT Analysis

The measurement of suspended sediment fluxes is well established in theory and practice. Measurements of bed-material load in large sand-bed streams and rivers have been practically nonexistent. The Helley-Smith bed-material load sampler has been shown to be somewhat effective in small streams and for gravel and cobble, but not in large sand-bed streams. Dutch researchers at the University of Utrecht have also developed a sampler that shows potential for use in large sand-bed rivers, but it has not been thoroughly tested on rivers like the Mississippi. Thus, until now, the ability to measure bed-load transport in large sand-bed rivers has been very elusive. A new method (ISSDOT) for measuring bed-load transport using multi-beam data was developed as a part of this MCNP monitoring program.

The ISSDOT method is currently being verified and refined through flume studies and comparisons to standard techniques for comparable conditions. The method's validity as a measure of absolute values of transport rates is being ascertained. Inquiries have arisen as to whether a *transport rate* or *gradient of transport* is actually being calculated. In Abraham and Pratt (2002), the transport parameter was termed a transport rate. However, when posing the ISSDOT method as a solution of the Exner Equation, it becomes clear that the change of volume and thus the change or gradient of transport is being measured, not the transport rate. Hence, the ordinates of the graphic results presented in Abraham and Pratt (2002) should be stated as Δq (i.e., q_2 minus q_1), and not as q, where q is the transport of bed material in the sand waves in mass per time per unit width of channel. It is interesting to note that Δq approaches q as the time step, or the interval between successive bathymetric plots, gets smaller. Further analysis will provide additional insight. Applying the ISSDOT method to several real river examples has shown that the method can already be used in a relative sense. Because of the repeatability of the measurements and the consistency of the method, relative differences between two or more measurement events appear to quantify real changes (Abraham and Hendrickson 2003). More measurements, experience, and statistical analysis must be made to verify this conclusion in a more rigorous sense.

Figure 11 shows the portion of the study area where detailed bathymetric data were collected during survey trip 2. It was during this survey (9–10 July 2001) that the water surface was drawn down in Pool 8. Before drawdown, data had previously been acquired in June 2001 during survey trip 1.

Figure 11.   Contoured plot of cross-wise and longitudinal swaths of bathymetric data, Pool 8

In this area of Pool 8, the drawdown resulted in a lowering of the water surface by about 0.3 m (0.9 ft). Four horizontal (cross-channel) swaths were taken between 12:14 p.m. on July 9th and 11:46 a.m. on July 10th. The different combinations of time spans between swaths varied from 2.68 to 23.53 hr. The ISSDOT method was applied to these data, and the results obtained are shown in Figure 12. The value of Δq decreases with increasing time span because a larger number, as the time span increases, is dividing the quantity of measured material. Uncertainty exists as to whether this is the best manner to extract transport information. Additional research may be required to fully appreciate the significance of these parameters. For the present time, these numbers are being used as upper and lower bounds, with a simple numerical average being an acceptable estimate. Flume data and field data both indicate that the calculated Δq approaches q as Δt decreases. Also shown in Figure 12 are the data from survey trip 1, taken on 26 June 2001, only two weeks earlier. However, the flow rate through Lock and Dam No. 8 during survey trip 1 was about 2,747 cu m/sec (97,000 cu ft/sec) compared to about 1,670 cu m/sec (59,000 cu ft/sec) during survey trip 2. For survey trip 1 there was no drawdown, yet the flow rate through the dam was about 1.6 times greater than during survey trip 2. Figure 12 shows that the bed load, Δq, at the section of river represented by the brown swaths was clearly higher during survey trip 1. This is what would be expected if there had been no drawdown during survey trip 2. Since there was a drawdown during survey trip 2, and the flow rates during survey trip 1 and survey trip 2 were so different, it is difficult to determine precisely whether the drawdown caused any significant increase in sediment mobilization.
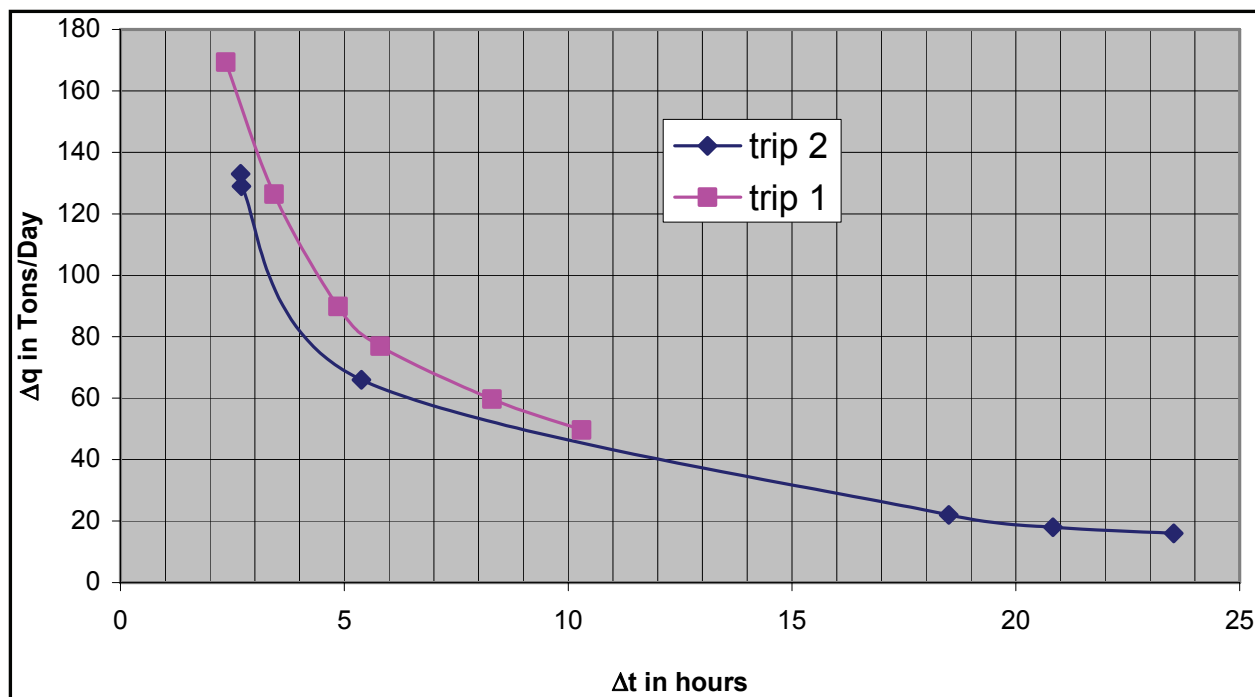
Figure 12. Δq versus Δt as computed using ISSDOT for Pool 8 conditions. The values are the average of 30 rows at each Δt

From the initiation of the project, and in planning the data collection, it was realized that to determine increases or decreases in sediment transport caused by the drawdown, it would be necessary to hold as many other variables constant as possible. The most important of these variables appeared to be flow rate. The river flow rates were not constant, however, and in survey trips 1, 2, and 3, the flow rates through Lock and Dam No. 8 were widely divergent. By carefully watching the St. Paul District website during late June of 2002, survey trip 4 data were collected at a flow rate through Lock and Dam No. 8 that was nearly the same as in survey trip 2. By that time, more analysis of ISSDOT method data had indicated that shorter time intervals between swaths would give results closer to an estimated "true" bed-load transport rate. So, the swaths for survey trip 4 were taken at about 30-min time intervals. This conclusion, however, was not known when survey trip 2 data were obtained. Figure 13 compares ISSDOT bed-load Δq computations for survey trip 2 (drawdown) and survey trip 4 (no drawdown).

In the legend of Figure 13, the first line indicates survey trip 4 Δq tons per day for a 0.3-m- (1-ft-) square grid. All lines in the legend use this convention. Grids that were 0.3 m (1 ft) and 0.6 m (2 ft) square were used for the computations to check the ISSDOT method spatial sensitivity. For these data and for those two grid sizes, there was minimal difference in the computational results. Considering the plotted values, the two data points for survey trip 2 data between the 2.5- and 3-hr time spans fall clearly above the data trend for the survey trip 4 data. Since both data sets were taken at nearly identical flow rates, it is hypothesized that the survey trip 2 data points do indeed indicate an increase in bed-load mobilization caused by the drawdown. Two data points are insufficient to assert any statistical significance, but these data, taken together with other

relevant data and analyses, strongly indicate that there is an increase of bed-load mobilization caused by the drawdown.
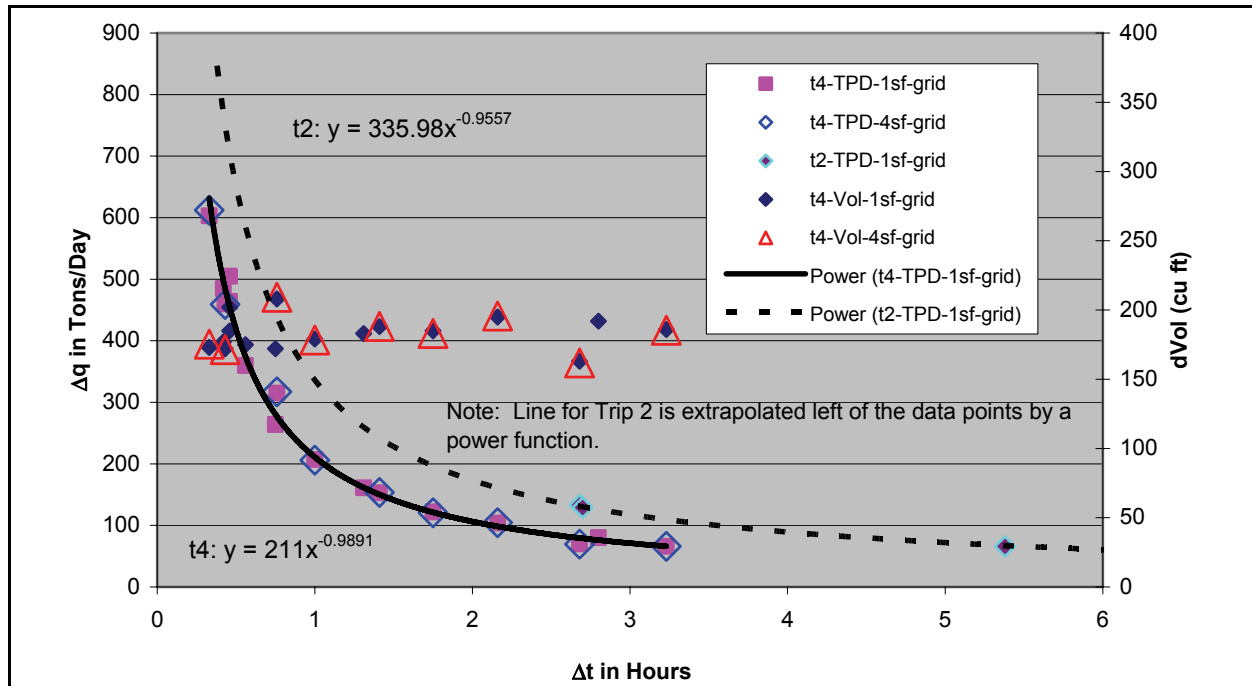
Figure 13. Δq versus Δt computed using ISSDOT for survey trip 2 (drawdown) and survey trip 4 (no drawdown). The change in volume used to compute Δq for each Δt is also shown. The values are the average of 30 rows at each Δt

It is important to check the ISSDOT method of computing bed-load transport, since it was used to arrive at the data plotted in Figures 12 and 13. The ISSDOT method is new and was developed during the course of this study. Preliminary results of field tests and a flume study indicate that the method is capable of determining the bed-load transport gradient (Δq) on large sand-bed rivers, subject to certain limitations. At the present time it is not entirely conclusive that the ISSDOT method provides a quantitative value for the true bed-load transport rate of a large river. However, considering the way data are collected and analyzed, it indeed does appear to be able to quantify *relative differences* of transport gradients at a given location. The reason for this is the high quality and repeatability of the collected data, as well as the consistency in the application of the ISSDOT method. To illustrate this, consider the three data collection trips to Pool 8 in which there was no drawdown (survey trips 1, 3, and 4). The data obtained during these trips were taken with a downstream pool elevation at Lock and Dam No. 8 of about el 192.0 m (630.1 ft) to el 192.2 m (630.5 ft) NGVD. However, the flows through Lock and Dam No. 8 were significantly different for the three trips. Survey trips 1, 3, and 4 had flow rates of about 2,719 cu m/sec (96,000 cu ft/sec), 821 cu m/sec (29,000 cu ft/sec), and 1,671 cu m/sec (59,000 cu ft/sec), respectively. If the data collection and ISSDOT method are consistently accurate as believed, then the transport gradients should increase for increasing flow rates, all other factors being equal. The data in Figure 14 justify these considerations.
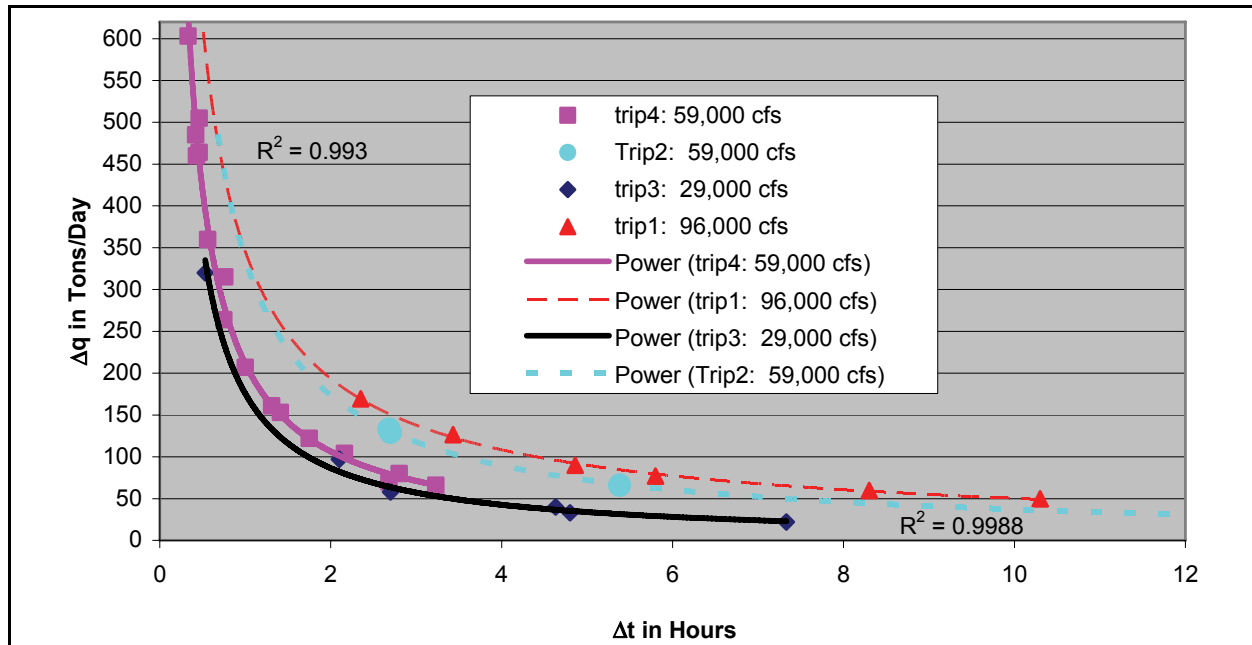
Figure 14. Δq versus Δt computed using ISSDOT for survey trips 1, 2, 3, and 4. The values are the average of 30 rows at each Δt

The values of Δq for survey trip 4 fall between those of survey trips 3 and 1. Clearly, for the three survey trips, Δq increases with increasing flow. Since curves were fitted through each data set, it is easy to see the differences. The method appears to be consistent in that, as flow rate increases, Δq increases. It also seems reasonable to allow that, for similar flow rates, the sand transport should be the same at a given site if all other factors are held constant. In the case of survey trips 2 and 4, the flow rates were indeed essentially identical. One factor not held constant was the drawdown. The drawdown was a reduction of the pool water level at Lock and Dam No. 8 of about 0.46 m (1.5 ft). In the vicinity of the study area near Brownsville, MN, this caused a local drawdown of about 0.3 m (0.9 ft). The data lines for survey trips 2 and 4 indicate clearly that the drawdown did in fact have a net effect of increasing Δq in the vicinity of the study area. This could be true not only because the cross-sectional area at the study site was reduced, but also because the percentage of total flow through this reach was increased because of the reduction in floodplain and distributary conveyance. Based on the limited data in Figure 14, the increase in bed-load transport would be about 30 percent more than normal pool transport.

Even though it appears that the drawdown affected bed-load transport in the study reach, because the ISSDOT method was still under development and refinement at that time and because the number of data points was minimal, it seemed prudent to apply other methods of analyses. Two other methods of ascertaining if the drawdown caused a net increase in transport were explored. One method analyzed and compared historical bathymetric data that the St. Paul District had collected with recent data collected during the drawdown. Another method used standard analytic sediment transport function computations.

Sediment Budget and GIS Analyses

Sediment budget analysis

In addition to the measurements made by ERDC during this study and used in the ISSDOT computations, the St. Paul District has been measuring sediment and hydraulic parameters on the Mississippi River for many years. These District data were collected as part of habitat improvement projects and navigation channel maintenance activities. Hendrickson (2003) developed an extensive sand budget for Pools 1 through 10 using available information on sediment transport at U.S. Geological Survey gaging stations, long-term channel dredging data, studies of sediment deposition, and hydraulic data.

The transport of sand-size sediment was of particular interest because of the expense associated with navigation channel dredging and because sand is the geomorphically dominant sediment size on the upper Mississippi River. Major planform changes on the river are associated with sand deposition in deltas or natural levees or with sand erosion from natural levees and islands. Sand is transported both as bed-load sediment and as suspended sediment, depending on local hydraulic conditions, so both modes of transport must be accounted for.

The results of the sand budget of Hendrickson (2003) are summarized in Table 2 of that document. That table is exceedingly comprehensive and lists data for many locations on the upper Mississippi River; it is not reproduced here. In the column titled "Sand Budget (tons per year)," the value of 182,500,160 kg/year (201,172 tons/year) is given for a location at Brownsville, MN. That number represents the estimated bed-material load in tons per year at that location, which is the ISSDOT study area. For that section of river, this would be the sand that moves along the bed in sand waves plus the suspended sand of the same size fractions. Because of the small channel slope (because of the pooling effect created by the locks and dams) and the medium sand size, it appears that the majority of bed-material transport occurs as bed load, i.e., as sand moving in sand waves. If 100 percent of the sand moved in sand waves, then a mean daily transport rate through this reach would be about 499,859 kg/day (551 tons/day). Even if only 50 percent of the bed-material load moved in the sand waves, then the mean daily transport rate would be about 249,476 kg/day (275 tons/day). These numbers fall within the range of values of Δq predicted by ISSDOT for survey trip 4 as Δt gets small. This would also be the case for survey trip 2 if that figure line were extrapolated. From a research point of view, it is plausible and probable that Δq approaches some estimated value of q as Δt gets small.

GIS analysis

The information in this section was extracted from Hendrickson and Hrdlicka (2003). The St. Paul District, using a multi-transducer survey boat whose position is tracked using a digital global positioning system, obtained hydrographic surveys of the main channel. Surveys were obtained from Lock and Dam 8 at River Mile 679.2 to Lock and Dam 7 at River Mile 702. The St. Paul District Geographic Information Center used Arcview software to create bathymetry models of the main channel between River Mile 686 and River Mile 691 to

determine the difference in bathymetry from one year to the next. This was done for 1998 to 2003 (except for 2000, for which data were not available).

Measurements of hydrodynamic and sediment parameters, and direct measurements of sand wave movement using the ISSDOT method, support the hypothesis of increased sediment transport during the drawdown. However, the GIS computations do not seem to indicate large-scale or long-term changes in main channel bathymetry during the drawdown.

Figure 15 shows that most changes between 2001 and 2002 fell within the range of 0.6 m (2 ft) of deposition to 0.6 m (2 ft) of erosion and probably represent typical bathymetric changes. There were a few areas where as much as 1.8 m (6 ft) of erosion or deposition occurred, but these were small and did not represent a large-scale trend. It is possible that channel degradation occurred during the actual drawdown and that the channel had filled back in before the surveys that were used in the GIS analysis were taken; however, channel maintenance personnel working in this area did not notice this kind of phenomenon.

Figure 15. Scour and deposition in the study area of interest in Pool 8

Figures 16 and 17 show the net main channel volume change and annual dredging between River Mile 686 and River Mile 691 for 1999 to 2003. The annual volumetric change for each river mile was obtained by generating difference plots based on surveys for each year. The survey dates were inconsistent from year to year. The 1999 surveys were done throughout the year, 2001 surveys were done in early October (well after the large amount of dredging done earlier in the year), 2002 surveys were done in late October, and 2003 surveys were taken from April to June. *Because of these inconsistencies, caution should be used in interpreting these results.* For example, surveys done early in the navigation season may show a shallower channel because of the spring

floods, while a survey later in the navigation season after dredging was
completed may show a deeper channel.
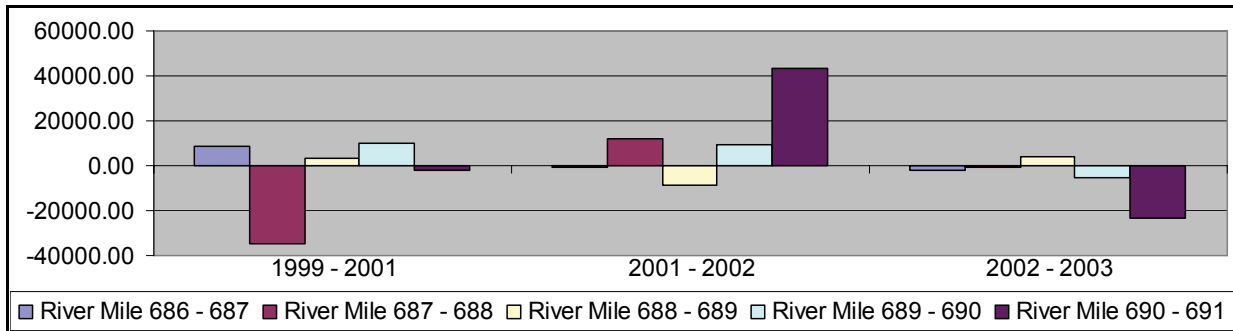
Figure 16. Main channel volume change (in cubic yards) by year for the study area of interest in Pool 8
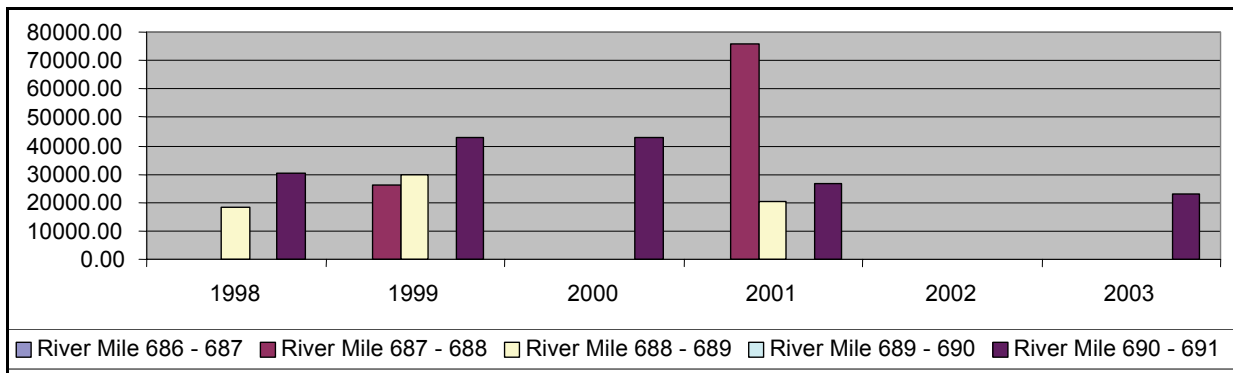
Figure 17. Dredging (in cubic yards) by year for the study area of interest in Pool 8

1999 to 2001. Figure 17 shows the large amount of channel dredging done in
June 2001 prior to the drawdown; 91,752 cu m (120,000 cu yd) were dredged in
2001, compared to a total of 160,566 cu m (210,000 cu yd) dredged in all the
other years shown. This dredging activity is partially reflected in the main
channel volume changes shown in Figure 16. Between River Mile 687 and River
Mile 688, there was a net degradation of about 26,761 cu m (35,000 cu yd),
which was due to the dredging that was done in June 2001. From River Mile 688
to River Mile 689 and from River Mile 690 to River Mile 691, about 15,292 cu m
(20,000 cu yd) and 19,115 cu m (25,000 cu yd), respectively, of sand were
dredged from each cut in June 2001 (Figure 17). However, both reaches are
dredged at this volume or greater annually, so the volume change analysis did not
indicate a significant change.

2001 to 2002. The volume change analysis also showed that between 2001
and 2002, over 30,584 cu m (40,000 cu yd) of deposition occurred between River
Mile 690 and River Mile 691. From River Mile 687 to River Mile 688 and from
River Mile 689 to River Mile 690, about 7,646 cu m (10,000 cu yd) of deposition
occurred in each reach. No dredging was needed in the study reach during this
time period.

2002 to 2003. Between 2002 and 2003, over 15,292 cu m (20,000 cu yd) of erosion occurred in the reach between River Miles 690 and River Mile 691. The dredging in this reach was done after the 2003 survey, so the erosion was not related to dredging. No other significant main channel volume changes occurred during this time period.

These are interesting results because this entire reach usually aggrades because of the spring floods, and yet there was little change in main channel bathymetry. The hydrodynamic conditions in Pool 8 during the drawdown that occurred in the summers of 2001 and 2002 should have resulted in increased sediment transport, and this is conceivably what kept the channel from aggrading.

The results of this GIS analysis cover time spans of three to four years and a river length of 8 km (5 miles). Therefore, this GIS analysis cannot be used for definitive statements regarding whether the drawdown affected local and temporary transport rates. It does, however, indicate that the regular cycles of scour, deposition, and dredging may have shifted towards erosion with less dredging. In the context of the ISSDOT measurements, it shows that there certainly could have been increased transport during the drawdown period but that such an increase and the effects from it were only temporary.

Transport Function Analysis

Analytic transport functions are another way to estimate bed-load transport in large sand-bed rivers. Many functions have been developed for a variety of river and flume conditions. These functions also compute different types of transport. For instance, some compute only total sediment load, others compute bed-material load, and yet others compute bed load only. The sediment and hydraulic analysis package Stable-channel Analytical Method (SAM) (Thomas, Copeland, and McComas 2002), developed at ERDC, was used to run the transport functions selected for this project. SAM can be accessed at web site http://chl.wes.army.mil/software/sam/. SAM is a windows-based package that allows users to select up to 20 transport functions. These functions have been programmed to accept the required hydraulic and sediment input data for each function. When executed with the appropriate data, each selected function will output its computed transport rate. Those functions that require the use of special graphs (e.g., Einstein's bed-load function) have those graphs programmed into the package. For the Pool 8 study, 17 of the functions were run, although only five of these can be used to compute bed load. These functions are listed in Table 2.

The five functions used to compute bed load are the following: Toffaleti, Meyer-Peter-Mueller [MPM (1948)], Schoklitsch, Einstein bed load, and Van Rijn bed load. The sediment and hydraulic data used as input to the transport functions are listed in Table 3. These data were not estimated but consisted of actual field measurements. For each trip, the data were collected as close in time as possible. This included bottom samples for the bed gradations and acoustic data to determine velocity profiles and discharge as well as to define the site cross section. The discharge measurements at the study site are not the same as

the flow through Lock and Dam No. 8, because the total flow through the lock and dam includes flow in the main channel as well as the floodplain and distributaries. Figure 18 shows the two cross sections at the time the measurements were made.

Table 2
Analytical Transport Function Computations

Function	Survey Trip 1		Survey Trip 2	
	Capacity, tons/day	Concentration, ppm	Capacity, tons/day	Concentration, ppm
Toffaleti	1,850	19	268	3
Toffaleti-Bedload	175		82.5	
Yang	1,490	15	219	2
Einstein (total)	919	9	526	6
Ackers-White	1,958	20	253	3
Colby	4,416	45	2,547	29
MPM (1948)	723	7	188	2
Laursen-Madden	1,998	20	235	3
Laursen-Copeland	3,677	37	852	10
Yang D50	1,352	14	202	2
Ackers-White D50	2,156	22	295	3
Schoklitsch (bed)	121.8	1.25	0	
MPM (1948) D50	973	10	220	2
Einstein bed load	653	7	399	5
Engelund-Hanson	3,096	32	643	7
Van Rijn	2,215	23	215	2
Van Rijn bed load	637.5		126.6	

Table 3
Hydraulic and Sediment Input Parameters for Transport Functions

Hydraulic Parameters		
Parameter	Survey Trip 2	Survey Trip 4
Flow, cfs	35,893	31,971
Water slope, ft/ft	0.00007	0.00003
Water surface elevation, ft	630.38	632.23
Cross-section area, sq ft	1,5246	1,7485
Average channel velocity, ft/sec	2.35	1.83

Average Sediment Characteristics			
Survey Trip 2		Survey Trip 4	
Percent Finer	Grain Size, mm	Percent Finer	Grain Size, mm
d_{05}	0.18	d_{50}	0.35
d_{10}	0.21	d_{60}	0.44
d_{20}	0.24	d_{70}	0.78
d_{30}	0.27	d_{80}	1.26
d_{40}	0.31	d_{95}	1.79
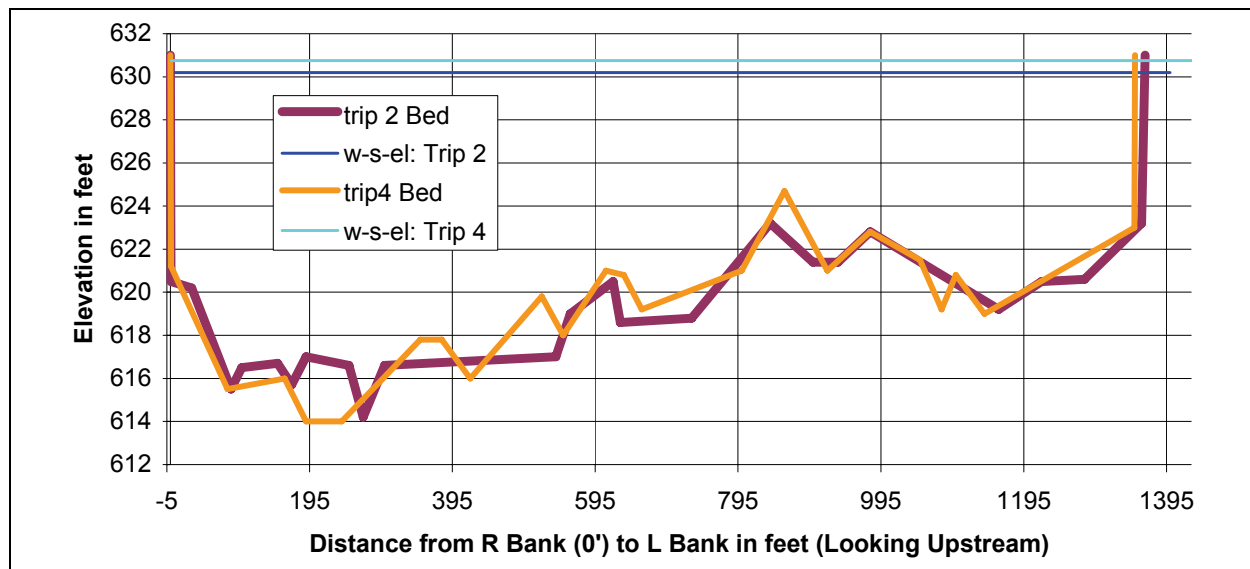
Figure 18. Comparison of channel cross sections in the study area for survey trips 2 and 4

The computed values of bed-load transport (i.e., the portion of bed-material load estimated or represented as moving in the sand waves) are shown in Figure 19.
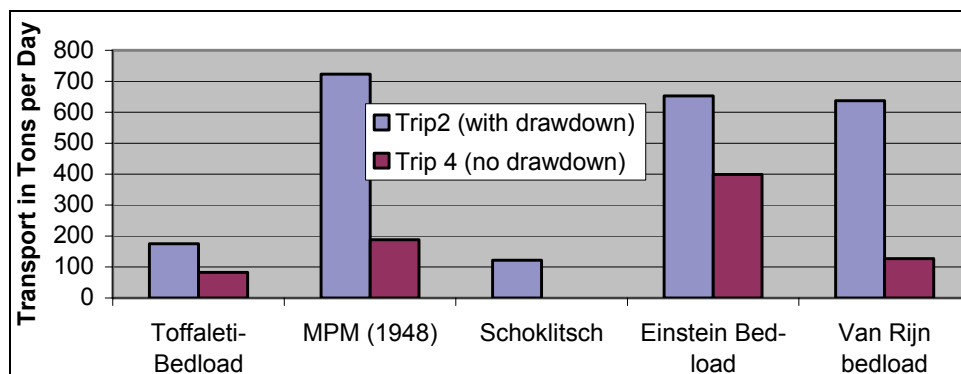
Figure 19. Results of transport function calculations for bed-load transport through the study reach of interest in Pool 8

Two significant results shown in Figure 19 should be emphasized. The first is that the magnitudes of the transport rates fall within the same range as Δq computed using ISSDOT. For survey trip 2, when the line in Figure 14 is extrapolated as shown, its highest values are in the range of 544,310–725,745 kg/day (600–800 tons/day, respectively). For survey trip 4, the highest values are approximately 544,310 kg/day (600 tons/day). The low values for each trip are near 36,285 kg/day (40 tons/day). Since it has been reasonably verified and adequately shown that the Δq computed by ISSDOT really does approach the transport rate for small Δt values, then these ISSDOT values compare very favorably with the computed transport function values.

The second significant result of importance is the consistency of the relative values of transport for survey trip 2 compared to those for survey trip 4. All five functions show significantly more transport for the drawdown condition (survey trip 2) than for the normal pool condition (survey trip 4).

Conclusions

For the same set of hydraulic and sediment characteristics, both the ISSDOT method of computing bed-load transport gradient and the analytic transport functions computed transport gradients/rates between 36,285 and 725,745 kg/day (40 and 800 tons/day, respectively) through the study reach. In each method, the lower values corresponded to the normal pool condition and the higher transport values corresponded to the drawdown conditions. Supporting these data, the sand budget analysis provided an estimate of a mean daily transport rate of bed load between 249,475 and 498,950 kg/day (275 and 550 tons/day, respectively). The transport rates for this case depend on the amount of bed material that can be proven to be in suspension.

Three sets of bed-load transport measurement data have been presented. They were each computed independently of one another. They also were derived using very different methods. Yet all three methods produced logical and reasonable results, and all are within an order of magnitude of each other. These data suggest the following conclusions regarding drawdown of the area of interest of Pool 8 on the upper Mississippi River during the summer of 2001. The observed drawdown did indeed increase sediment mobilization within the study reach. Additionally, the original wing dam structures as designed, and in conjunction with a drawdown, continue to positively influence sediment movement in the reach. Conversely, as pool levels are increased, the structures will have a diminishing effect in mobilizing sediment through the reach. Through further monitoring to establish base transport rates, it will be possible to project sediment movement before, during, and after such events. By utilizing ISSDOT technology and other river management information gleaned from this monitoring study, river managers could more efficiently plan their dredging requirements for events such as the Pool 8 drawdown.

4 Numerical Analysis of Effects of Drawdown and Wing Dam Structures on Shear Stress in Pool 8 Navigation Channel

Three sets of bed-load computational data were produced using the ISSDOT method, a sediment budget and GIS analysis, and analytic sediment transport functions. A numerical simulation model called ADaptive Hydraulics (ADH) was adapted and applied to the same study area. The purpose of this additional computational analysis was to determine if this model could further corroborate previous conclusions regarding the effects of a drawdown and wing dam structures on bed load and navigation channel topography at the region of interest in Pool 8 on the upper Mississippi River. ADH was applied only in the hydrodynamic mode to ascertain river bottom stresses. The numerical simulation model grid is shown in Figure 20.

Methodology

ADH is a finite element numerical model capable of running in two-dimension or three-dimension mode. An additional feature of this program is its ability to automatically change resolution in order to facilitate convergence in areas with a high solution gradient. When the computations are complete, the solution is provided at the locations of the original mesh. For the modeling effort at Pool 8, the high-resolution bathymetric data allowed for a very detailed mapping of the river bottom and, thus, an excellent representation of bottom elevations in the numerical mesh. The river bottom topographic contours are shown in Figure 21.

Figure 20. Numerical grid for ADH simulation of the area of interest in Pool 8

Chapter 4   Numerical Analysis of Effects of Drawdown
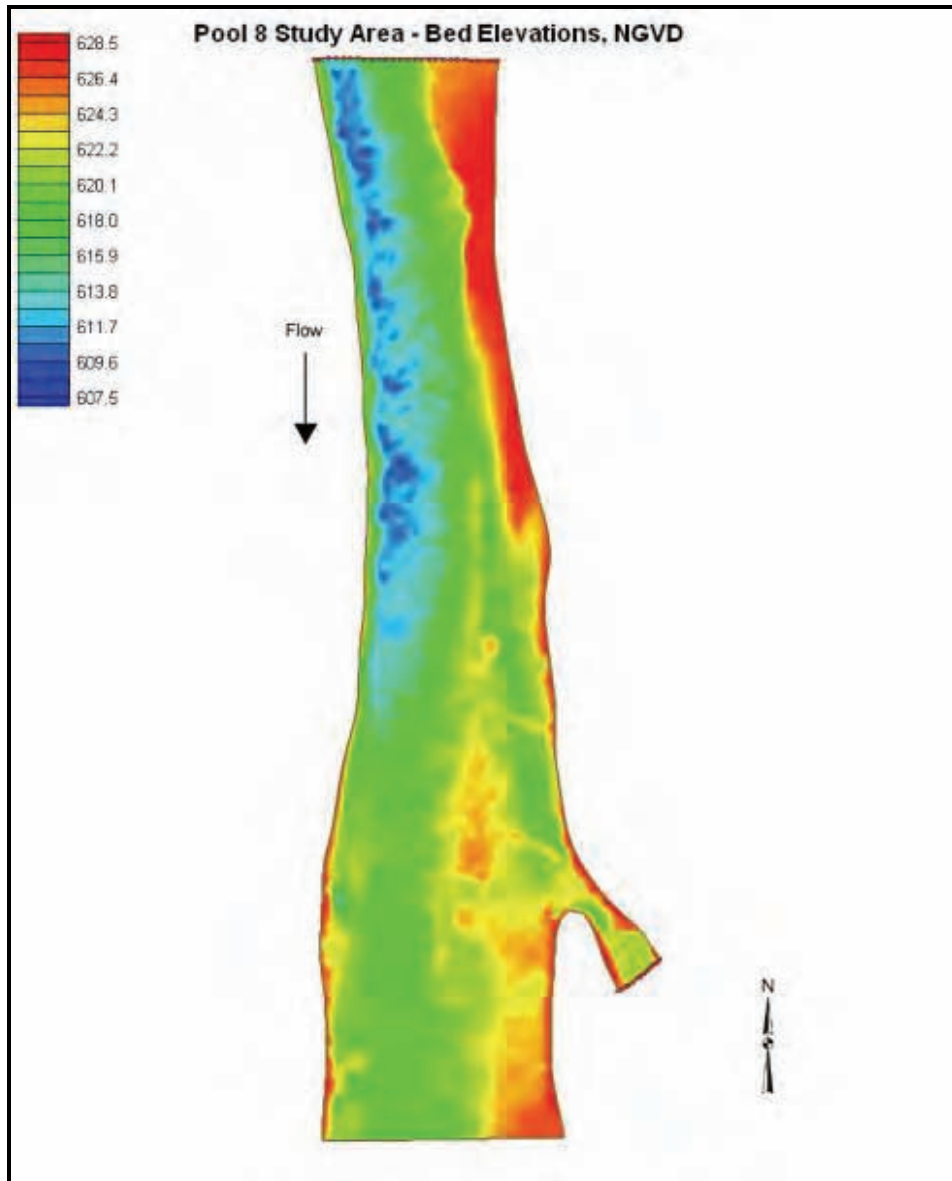
Figure 21. Contours of the study reach bathymetric elevations, Pool 8, upper Mississippi River

For comparison of the effects of the drawdown on sediment transport, the data taken in July 2001 (survey trip 2) and June 2002 (survey trip 4) were used in this numerical analysis. The flow rate through Lock and Dam No. 8 was nearly the same for both of these data surveys; thus, any measurable changes in sediment transport characteristics would be caused by factors other than flow. The numerical model was run for all four survey data sets, but only the data from survey trips 2 and 4 are compared in this report. All computational runs converged well, as in the case of the survey trip 2 depth convergence plot shown in Figure 22.
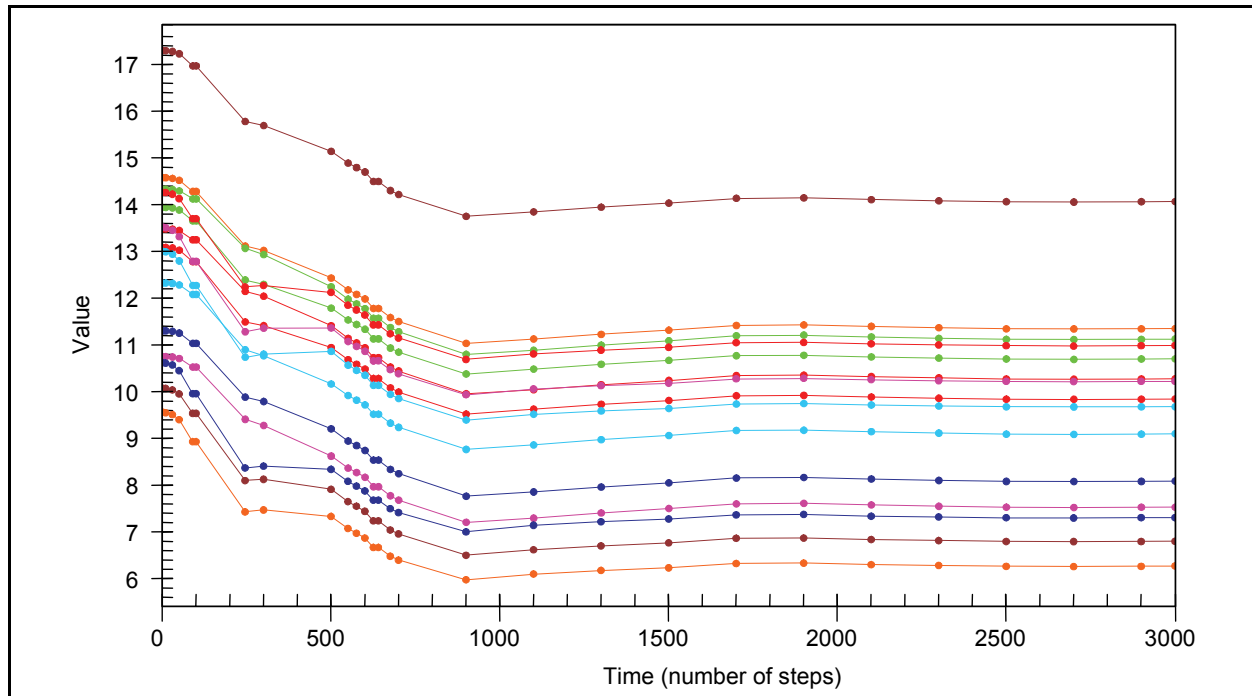
Figure 22. Computed water depth convergence for selected nodes for survey trip 2 at Pool 8

Figure 22 shows the convergence of water depth for various selected nodes throughout the mesh. Once the lines become horizontal, they indicate small changes in depth from one computational time step to the next. This in turn shows small errors and, thus, a well-converged solution. In this case, after 1,000 time steps the computations were approaching the correct solution, and after 2,000 time steps they could be considered well converged.

For both survey trip computations, Table 4 shows the upstream boundary condition specified as an inflow, and the downstream boundary condition as a tail water elevation and a side channel outflow. The upstream inflows are not exactly equal, even though the flow through Lock and Dam No. 8 was nearly the same for survey trips 2 and 4 at the times the measurements were made. That is because the total flow through the lock and dam includes flow in the main channel as well as flow in the floodplain and distributaries. The drawdown forced more of this flow through the main channel. The measured and computed water surface slopes compare well for both computational runs.

Table 4 ADH Model Input Parameters and Slope Verification					
Survey Trip	Inflow at Upstream Boundary, cfs	Side Channel Outflow, cfs	Downstream Tailwater Elevation, ft	Measured Water Surface Slope	Computed Water Surface Slope
1	56,267	6,584	632.78	0.000081	0.000082
2	35,893	3,664	630.0896	0.000079	0.000077
3	12,473	1,242	630.7631	0.0000053	0.0000055
4	31,971	3,696	631.0849	0.000038	0.0000397

To arrive at meaningful conclusions about the mobility of sediment for a drawdown condition versus a no-drawdown condition, certain parameter must be measured. In this case, no tested and verified sediment routine for the upper Mississippi River was available in the ADH code at the time these numerical computations were being made. Instead, the shear stress produced on the bottom of the river was selected as an indicator of sediment mobilization. This shear stress value was computed for each nodal location of the computational mesh of Figure 20 for data from both survey trips 2 and 4. These values were then contoured to show their spatial distribution throughout the study area for both survey trips.

The results of the shear computations are shown in Figure 23 and Figure 24 for survey trips 2 and 4, respectively. Both plots are contoured with the same color scale so that the difference in bottom shear stress can easily be detected. It is clear from these figures that the shear stresses during the survey trip 2 drawdown condition were higher than those during normal pool operation as measured by survey trip 4 data. Figure 25 shows the differences in greater detail by subtracting the shear stress values of the survey trip 4 data from those of the survey trip 2 data.

The high shear stress at the upstream end of the model is due to the imposed inflow boundary conditions and should not be considered. Otherwise, the spatial distribution and relative magnitudes of computed shear are considered to be representative of what would be measured in the river, i.e., if it were possible to directly measure shear on the bottom of a river in such detail. In this case the relative values would be representative of the difference in shear between survey trip 2 and survey trip 4 data. Positive values in the difference plot of Figure 25 indicate higher values of shear in the survey trip 2 data. (All values of shear in this display are positive.) Also, during this drawdown, Figure 25 clearly shows the effect that the structures are still having on mobilizing sediment in what is otherwise a depositional reach. For the reach of interest of Pool 8 on the upper Mississippi River, the drawdown condition definitely produced a greater potential to entrain and transport sediment than when the dams are operated at normal pool elevations. Other portions of the pool may react differently.

Conclusions

The performance of wing dam training structures for increasing sediment transport through the river reach of interest of Pool 8 during a water level drawdown was by Abraham and Hendrickson (2003), who discussed three methodologies. That investigation showed that the structures, in combination with the water level drawdown, did indeed positively influence sediment movement in the reach. This fourth analysis effort, using the same data, came to the same conclusion but by using a different tool. This tool is a two-dimensional hydrodynamic numerical model, ADH. The additional detail available by using the numerical model ADH rather than other analytical techniques is obviously apparent by analyzing the information contained in Figure 25, for example. Though the numerical model requires more time, effort, and data for execution than the other analysis techniques, it is worth the extra effort when detailed temporal and/or spatial information is required in a given study reach.
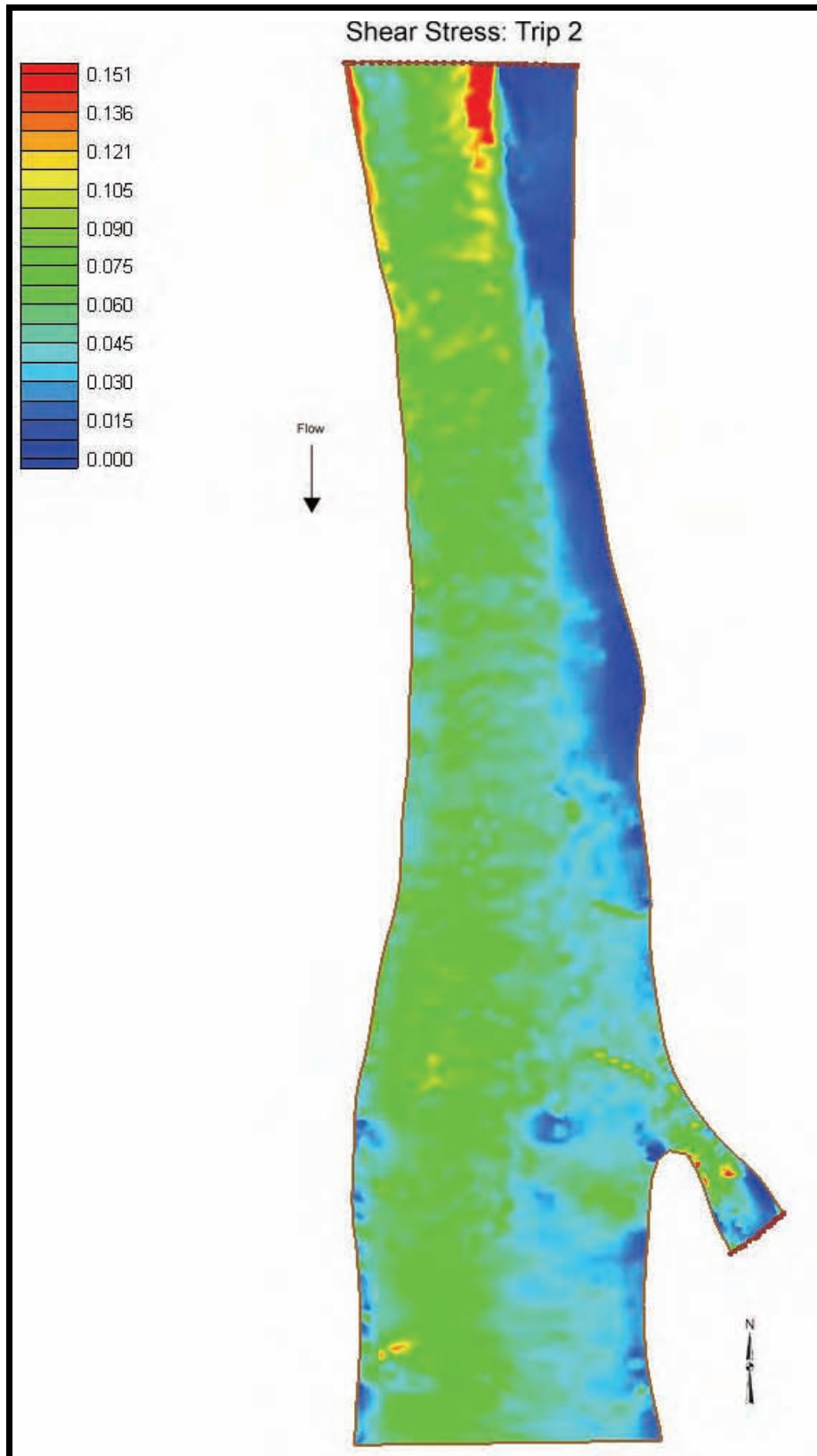
Figure 23. Contours of ADH-computed bottom shear stress (lb/sq ft), survey trip 2
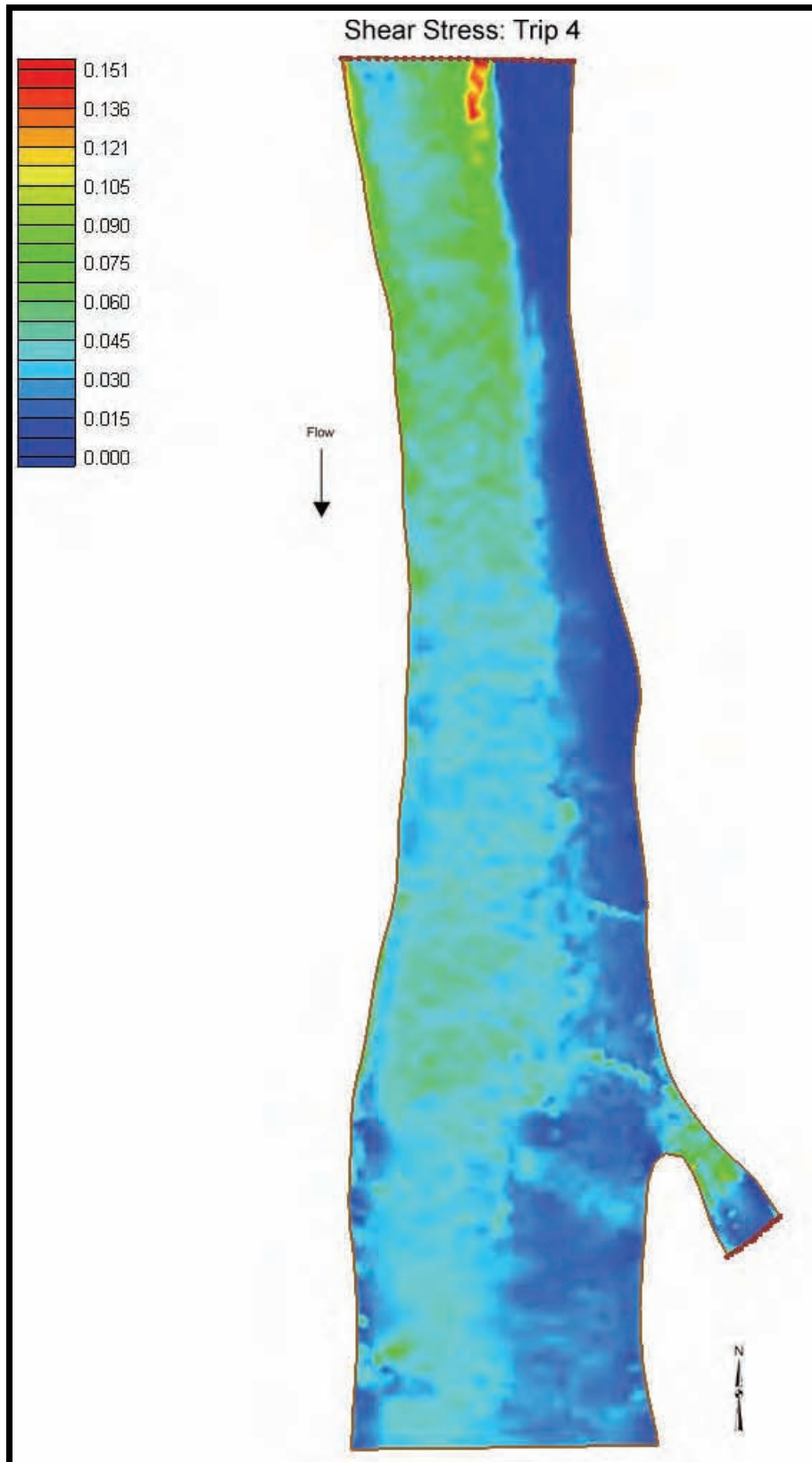
Figure 24. Contours of ADH-computed bottom shear stress (lb/sq ft), survey trip 4
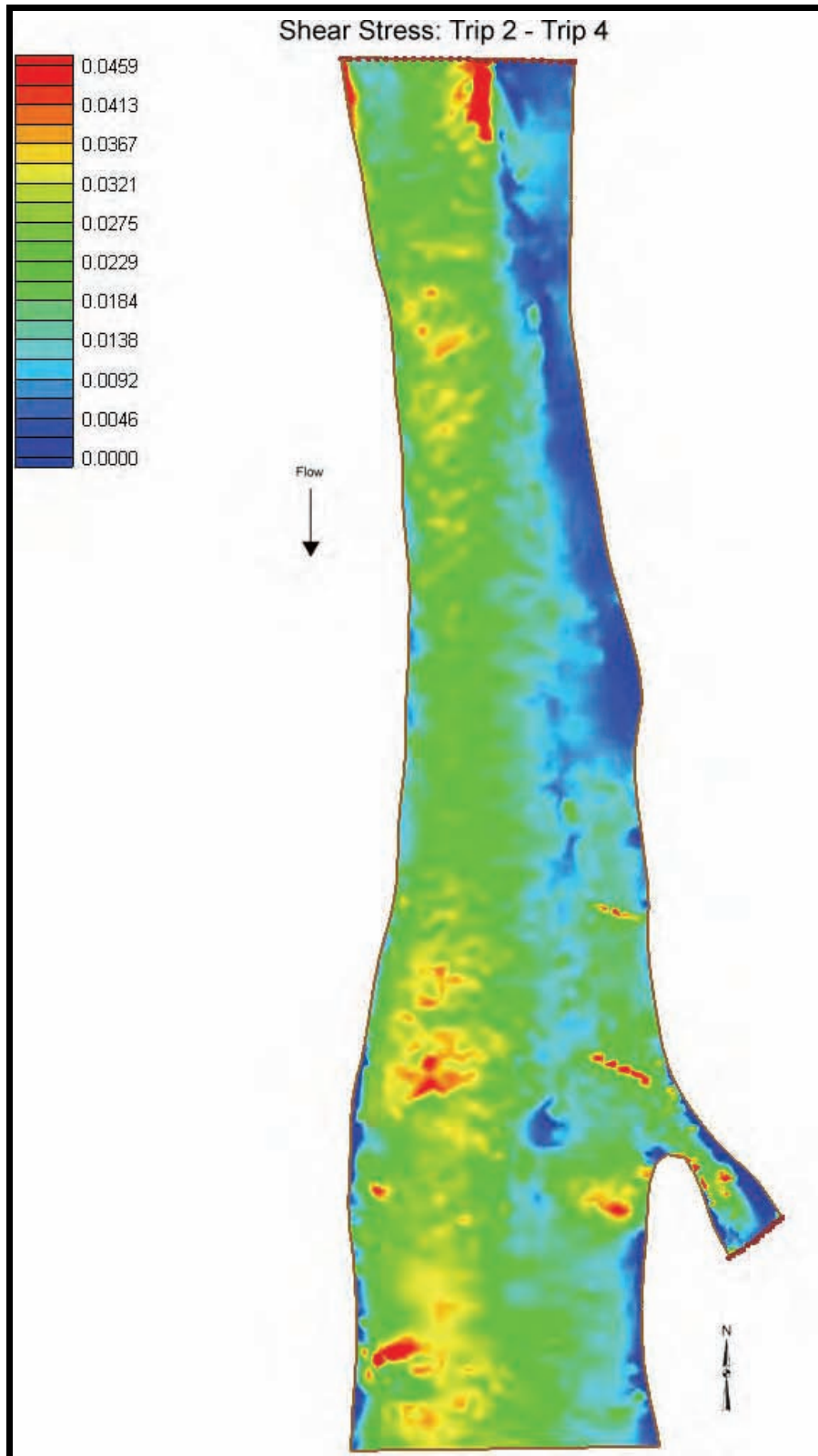
Figure 25. Difference value plot of ADH-computed bottom shear stress (lb/sq ft) for survey trip 2 minus survey trip 4

5 Effects of Closure Dams on Navigation Channel and Back Channel Characteristics in Pool 13

Monitoring studies to evaluate the performance of closure dam channel training structures placed in Pool 13 of the upper Mississippi River are presented. The closure dams were placed in the river in April 2001. The river navigation channel and back channel characteristics were monitored for about 2.5 years after the placement of the closure dams. Monitoring consisted of measurements of the bathymetric and hydraulic changes that took place during this interval. The information assembled was used to evaluate the initial performance of the closure dam training structures.

Purpose of the Closure Dams

The study area is located near Savanna Bay at River Mile 539.0 (Figure 26). Lock and Dam No. 13 is located 26.7 km (16.6 miles) downstream of the study area, at River Mile 522.4. The U.S. Army Engineer District, Rock Island, has performed a substantial amount of historical and modern day dredging in this reach of the river to maintain the authorized navigation channel. The channel thalweg near Savanna lies along the outside of a sharp-radius bend through this area. A depositional bar forms along the inside of the bend, restricting the available width through the reach. This area of deposition is shown by the location of historical dredge cuts, which can be seen as the red and pink areas in the figure. The green indicates the location of historical placement sites.

A series of closing structures were designed and constructed to reduce the amount of flow through the back channels behind the islands and thereby increase the velocities in the main channel to reduce sediment deposition and encourage a more reliable navigation channel that would require less maintenance dredging in the future. The upper two closure dams were built to 1.5 m (5 ft) below the flat pool, and the lower dam is emergent. Figure 27 shows the bathymetric features of the study area, the main channel, the back channel, and the islands.

Early in the planning stages of the project a concern was raised that the reduced flow in the back channel could induce sedimentation behind the islands and result in a loss of valuable over-wintering habitat for fish. To address this concern, numerical modeling, flow visualization, and micro-modeling were performed by the Rock Island and St. Louis Districts to evaluate the sediment transport and hydrodynamic response trends that could be expected to occur from construction of the closure dams (Kirkeeng et al. 1998). Results of the model effort indicated that construction of the closure dams would not result in significant sedimentation in the back channel area.
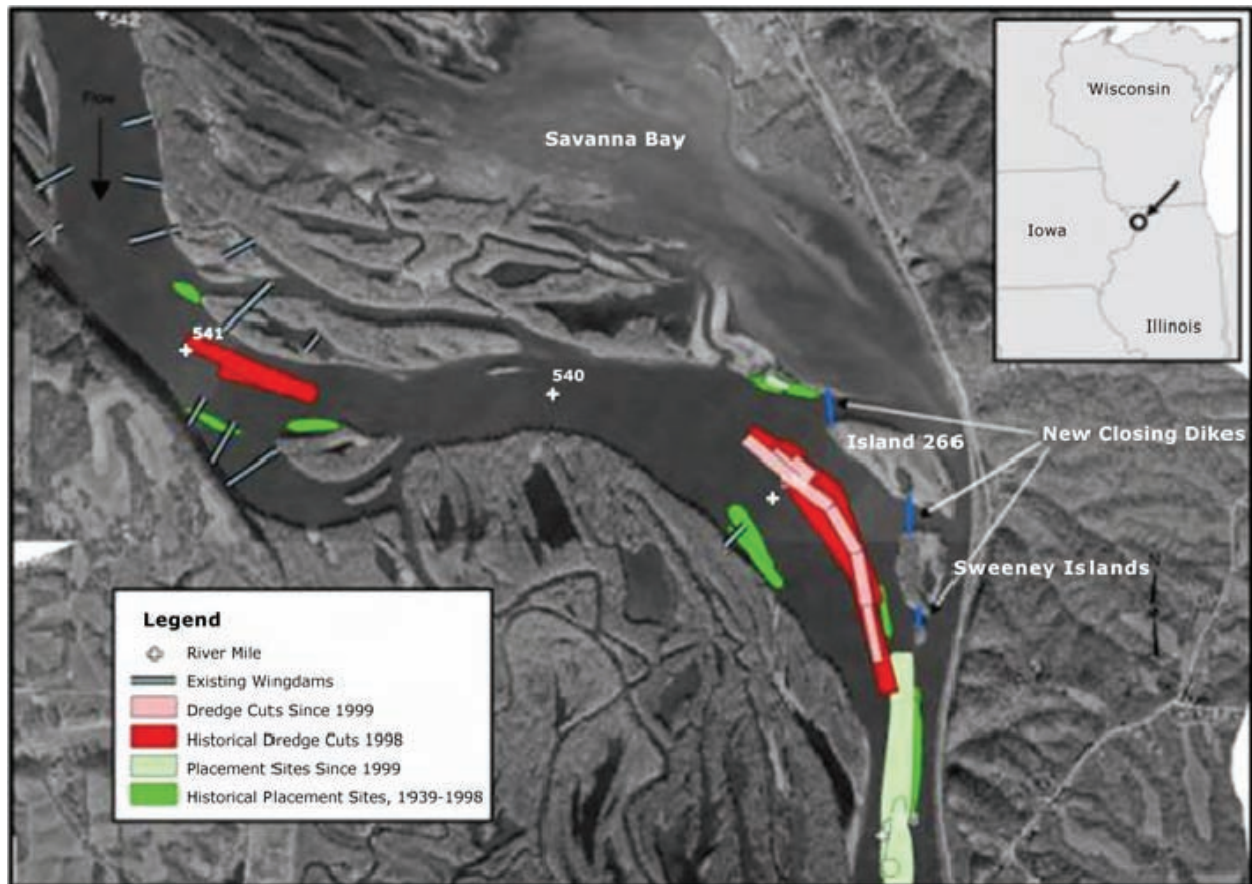
Figure 26. Location map, historical dredging locations, and new closure dams
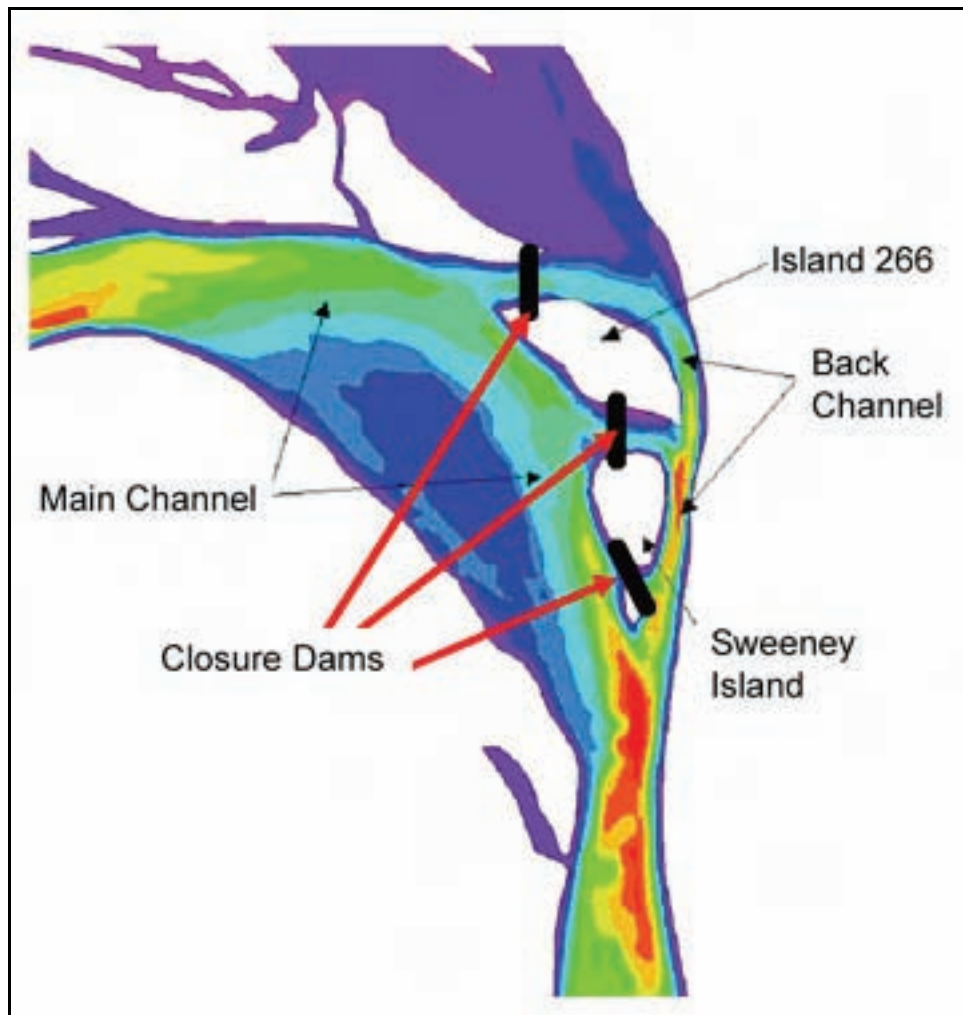
Figure 27. Pool 13 study site feature identification

Analysis Methodology

There are several techniques that could be employed to measure the effectiveness of the closure dams, including bathymetric, hydraulic, and biological metrics. The purpose of the closure dams was to decrease sedimentation in the main channel while not causing significant sedimentation in the back channel. The analysis method selected for implementation was to perform bathymetric and hydraulic surveys at various time intervals after construction of the closure dams. Changes observed during the monitoring time could then be used to determine whether or not the dams are performing as desired. Field data collection survey trips were planned and executed.

The closure dams were completed in April 2001. The first field data collection survey was made in November 2001 (survey trip 1). This survey consisted of multi-beam bathymetric data, discharge and velocity data, and sediment samples. Figure 28 shows the survey boat from which all the data were

collected. This vessel serves as a platform for the multi-beam bottom profiler, the ADCP current profiler, and winch and crane assemblies for suspended and bottom sediment samplers. It is equipped with that a GPS that fully compensates for pitch, heave, and roll. On-board computers process input from the ship gyroscope, GPS, and sensors to provide time-tagged three-dimensional coordinates for all the data collected from these sensors. Figure 28 shows the survey boat with the multi-beam sensor underwater collecting bathymetric data. There are 32 transducers in the sensor head, which assure excellent bathymetric resolution. For the Pool 13 monitoring study, the bathymetric data were processed onto a 0.9-m- (3-ft-) × 0.9-m- (3-ft-) square grid.

Figure 28. Field data collection survey vessel at the region of interest in Pool 13, upper Mississippi River

Additional surveys were made in June 2002 (survey trip 2) and July 2004 (survey trip 4), using the same vessel and equipment. As much as feasible, the data were collected at the same locations so that comparisons of changes in hydraulic and bathymetric features would be valid.

Results

Bathymetric surveys were processed and analyzed. Figure 29 shows the main channel bathymetry mapped in November 2001 (survey trip 1), shortly after the closure dams were placed. Figure 30 shows the main channel bathymetry mapped July 2004 (survey trip 4), about 2 years and 9 month following survey trip 1. The locations of the deepest parts of the channel remain essentially unchanged; however, it is difficult to draw quantitative conclusions by visual observation of these figures. Further data analyses are necessary.

Chapter 5 Effects of Closure Dams on Navigation Channel and Back Channel Characteristics in Pool 13

To make better quantitative assessments, the study site was divided into two distinct reaches: the main channel just west of the islands, and the back channel just east of the islands. The main channel was further subdivided into three sections called Area 1, Area 2, and Area 3 (Figure 31).

Similarly the back channel was subdivided into two sections called Area 1 and Area 2 (Figure 32). The locations were chosen because they represent the deepest water in each reach and also because these locations were of prime interest during planning and initiation of the study. The closure dams were constructed to increase flow in the main channel so as to maintain or possibly increase the main channel depth while at the same time not causing any deposition in the back channel. Therefore, the effectiveness of the dams can best be evaluated by focusing the analysis on these five areas.

For each area in a given reach, a dense grid of bathymetric elevations was available. To determine if any overall change in bottom elevation in a given area occurred in the time between when any two data sets were taken, the entire data set was examined instead of examining elevation differences at specific point locations. Nothing can be inferred about bathymetric changes at any set location because each of these elevation data sets is simply a snapshot in time. At any given location, the elevation of the bottom will change with the periodicity and amplitude of the sand waves. Examining single elevation differences between two coincidental spatial locations is not very informative.

By contrast, examining all the data points in an entire area can yield very meaningful quantitative information. For instance, if in the main channel between survey trip 1 and survey trip 4, the average elevation of all data points decreased, then one could conclude that the channel bed lowered, or was scoured. If all data points showed an increase, then a net deposition would be inferred. Using this approach, the following information was computed and tabulated for the five areas using the collected bathymetric data from survey trips 1, 2, and 4 (Table 5). (Instrumentation malfunction during survey trip 3 prevented enough data collection to be meaningfully included in this analysis.) The data indicate some apparent scour and deposition trends, as shown in the right column of the table.
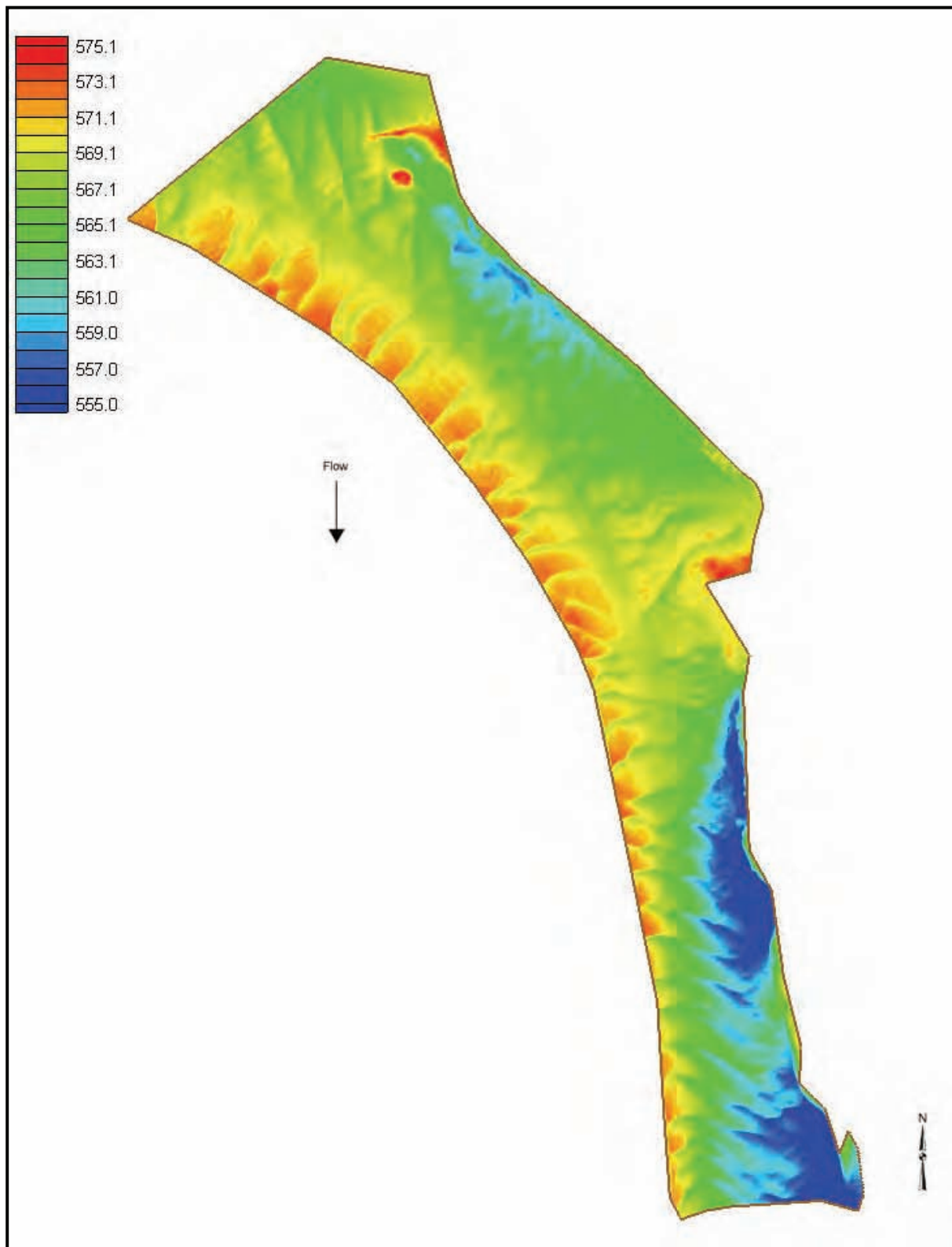
Figure 29.   Survey trip 1 main channel bathymetry for the region of interest in Pool 12, Upper
Mississippi River
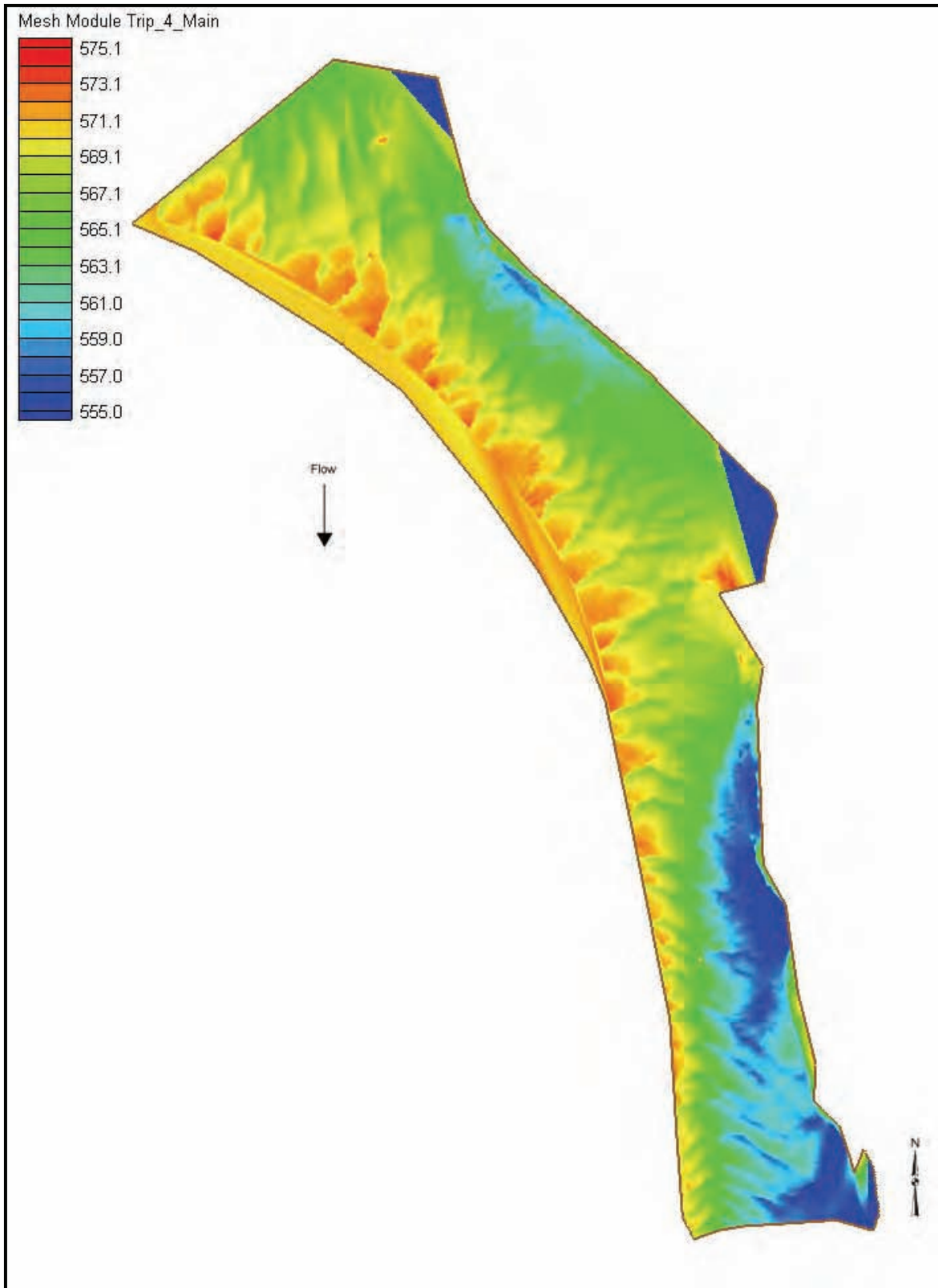
Figure 30.   Survey trip 4 main channel bathymetry for the region of interest in Pool 13, upper Mississippi River
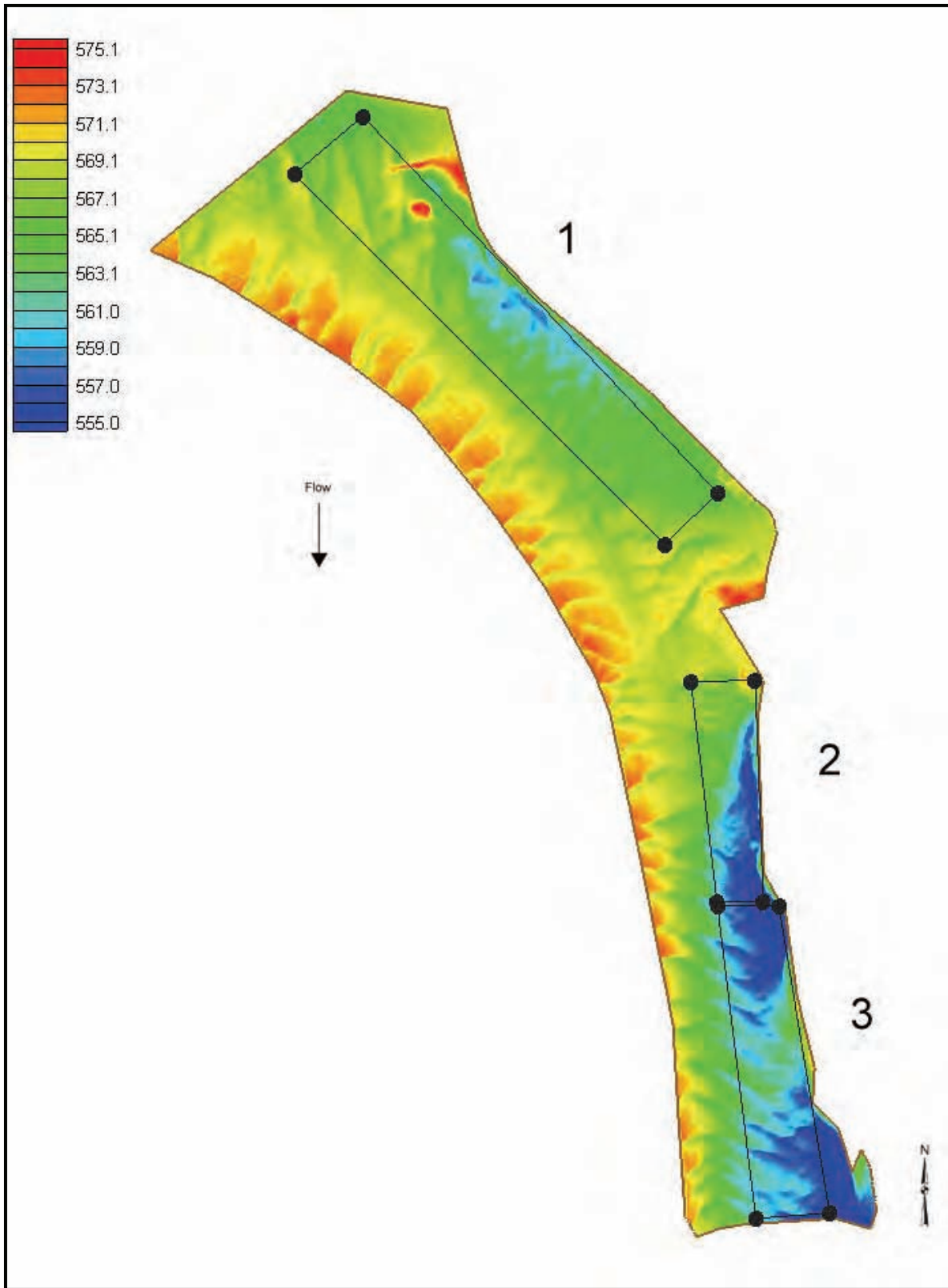
Figure 31.   Main channel division into Area 1, Area 2, and Area 3
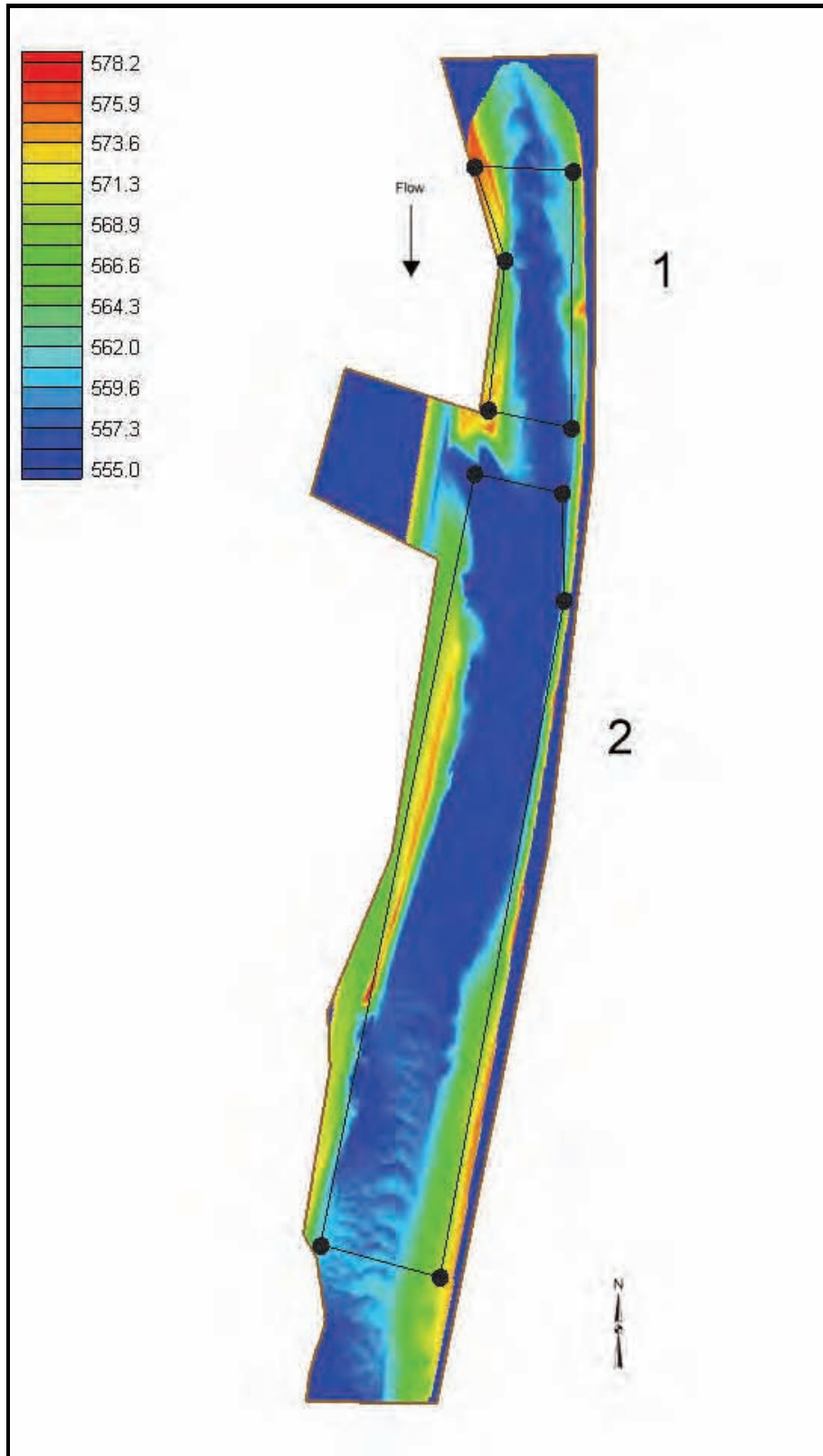
Figure 32.   Back channel division into Area 1 and Area 2

Table 5
Results of Field Data Survey Analysis

	# of Data Points	Avg Bott. Elev	Comparison	Δ Elev (Ft)
Main Channel				
Area 1 Trip 1	64154	565.224	Trip 2 - Trip 1 elevs.	-0.066
Area 1 Trip 2	64154	565.158	Trip 4 - Trip 2 elevs.	0.089
Area 1 Trip 4	64154	565.247	Trip 4 - Trip 1 elevs.	0.023
Area 2 Trip 1	18467	561.219	Trip 2 - Trip 1 elevs.	-0.233
Area 2 Trip 2	18467	560.986	Trip 4 - Trip 2 elevs.	0.18
Area 2 Trip 4	18467	561.166	Trip 4 - Trip 1 elevs.	-0.053
Area 3 Trip 1	31869	558.633	Trip 2 - Trip 1 elevs.	-0.536
Area 3 Trip 2	31869	558.097	Trip 4 - Trip 2 elevs.	0.37
Area 3 Trip 4	31869	558.467	Trip 4 - Trip 1 elevs.	-0.166
Back Channel				
Area 1 Trip 1	5178	N/A	Trip 2 - Trip 1 elevs.	N/A
Area 1 Trip 2	5178	557.914	Trip 4 - Trip 2 elevs.	0.466
Area 1 Trip 4	5178	558.38	Trip 4 - Trip 1 elevs.	N/A
Area 2 Trip 1	25754	555.508	Trip 2 - Trip 1 elevs.	0.352
Area 2 Trip 2	25754	555.86	Trip 4 - Trip 2 elevs.	0.71
Area 2 Trip 4	25754	556.57	Trip 4 - Trip 1 elevs.	1.062

To help display the changes shown in Table 5, plots of elevation percentile curves were produced; these curves can be seen in Appendix A. However, some of the vertical changes in elevations are relatively small and hard to see in these graphs. Therefore, before any conclusions are put forth, the significance of the elevation changes should be addressed. To do this, an analysis of variance (ANOVA) was performed on the same data sets as in Table 5. Johnson, Miller, and Freund (1994) provide a discussion and equations related to ANOVA analysis. The results of the ANOVA also are presented in Appendix A. These results show that in all but two cases, the differences in the depth measurements, and thus the change in elevation, were statistically significant at the 95 percent confidence level.

Conclusions

From the foregoing tables, graphs, and analysis, the following conclusions can be deduced. For the main channel, Area 1 and Area 2 showed a scour trend between November 2001 and June 2002. From June 2002 to July 2004, both areas showed a deposition trend. Thus, short-term occurrences of scour and then redeposition were measurable and statistically significant at the 95 percent confidence interval. However, over the entire monitoring period of November 2001 to July 2004, the net result showed no discernable change in the main channel bathymetry with regard to average depths in Area 1 and Area 2. This is statistically shown in Appendix 1 by the acceptance of the null hypothesis for the Main Channel Study Area 1 and Area 2 (survey trip 1 versus survey trip 4).

Area 3 of the main channel showed the same trend of scour and then deposition as Area 1 and Area 2 for the same time periods. However, over the entire monitoring period, the net result was a discernable scour trend.

For the main channel, Area 1, Area 2, and Area 3 all had the same trend of scour first and then redeposition. The only difference between them was that in Area 3 the redeposition was not as much and, thus, still showed a measurable difference (slight scour) between the first and last surveys. Whether the redeposition trend will continue in all three areas cannot be determined from these data.

For the back channel Area 1, there was only one "difference" data set. It showed a net deposition trend of nearly 0.15 m (0.5 ft) between June 2002 and July 2004. In Area 2 of the back channel, all measurements show a net deposition trend, with the maximum being about 0.34 m (1.1 ft) over the entire survey period of 32 months. The net deposition in the back channel is statistically significant at the 95 percent confidence interval. As in the main channel, whether the deposition in the back channel will continue cannot be determined from these data.

This MCNP monitoring investigation has provided a quantitative measure of the bathymetric changes in the study area of interest of Pool 13 on the upper Mississippi River after the closure dam training structures were installed. This successful study has been possible through careful analysis of high-resolution bathymetric surveys. The data show spatial and temporal scour and deposition trends in the study area and also address the statistical significance of each.

6   Summary and Conclusions

Summary

Channel training structures (wing dams and closure dams) that are currently in place on the upper Mississippi River were constructed more than 100 years ago to increase flow in the navigation channel and cause scour to occur, resulting in a deeper channel. Initially, these structures accomplished this goal, as evidenced by the islands and sandbars that formed around them. The construction of the locks and dams 60 years ago submerged the training structures, reducing their effectiveness and increasing secondary channel and floodplain conveyance.

In cooperation with the U.S. Fish and Wildlife Service (USFWS) and the Departments of Natural Resources from Minnesota and Wisconsin, the U.S. Army Engineer District, St. Paul, executed a drawdown of Pool 8 (upstream of Lock and Dam No. 8) on the upper Mississippi River near La Crosse, WI, during the summers of 2001 and 2002. Water levels were allowed to drop below normal minimum values at Lock and Dam No. 8 to expose mud flats, promote seed germination, and benefit fish and wildlife. Lowering water levels during a drawdown decreases wing dam training structure submergence and floodplain conveyance and alters flow patterns between and around the training structures. This could have resulted in sediment mobilization and scour in the navigation channel.

During the spring of 2001, three closure dams were constructed in Pool 13 (upstream of Lock and Dam No. 13) near Savanna, IL. The first closure dam is located immediately north of Island No. 266, the second is immediately north of Sweeney Island, and the third is immediately south of Sweeney Island. These closure dams are actually submerged weirs that should allow water to continue to flow into the backwater areas of these two islands in Pool 13, but at reduced quantities. At issue is whether the main channel might require reduced dredging in future years as a result of the construction of the closure dams and also whether the backwaters of the eastern side of the islands will fill with sediment.

Development of ISSDOT

The need for quantifying bed-load transport is universal in riverine and coastal process studies. In the past, many analytical and mechanical methods have been devised to try to quantify bed-load transport on large sand-bed rivers. Most of these methods have only been marginally successful. In this monitoring study, the ability to quantify the bed load accurately was essential in determining whether river training structures in combination with a drawdown of the

navigation pool would have a significant effect on net sediment movement through a given reach of river. Accurate measurements would resolve whether the altering of the pool stage and flow schedules might also be used as a sediment management tool. A new and expedient methodology for the computation of bed-load transport [Integrated Section Surface Difference Over Time (ISSDOT)] was developed using multi-beam bathymetric data. ISSDOT computational methodology has not been previously considered practical because the quality and quantity of multi-beam intensely detailed bathymetric data required to make this method work were not available until recently.

The section surface difference method processes multi-beam data and quantifies a bed-load transport rate for a given river cross section. This is accomplished by taking at least two sets of bathymetric data, at different times, for the same spatial location. The two data sets are interpolated to a spatial grid, and a difference plot is produced. Incremental volumes are calculated and summed over the entire cross section. The total volume change with time, when multiplied by the density of the water/sediment mixture, yields a mass transport rate.

The location of the monitoring site and study area used to develop the ISSDOT measurement technique was Pool 8. ISSDOT produced results that compared favorable with other standard analytical methods.

Effects of drawdown and wing dams on bed-load transport in Pool 8

Three methods were used to determine if net sediment movement occurred in the study reach of interest. The first method used detailed multi-beam bathymetric data taken in the vicinity of River Mile 689.2. These data were analyzed using ISSDOT. The second method used long-term data previously collected by the St. Paul District. These data included suspended sediment measurements and bathymetric data and were analyzed in the form of a sediment budget and through GIS manipulation. The third method used measured sediment and hydraulic data that were analyzed using sediment transport functions.

ISSDOT analysis. The data from survey trip 2 (July 2001) and survey trip 4 (June 2002) indicate clearly that the drawdown did in fact increase the flow rate in the vicinity of the study area. This could be true not only because the cross-sectional area at the study site was reduced, but also because the percentage of total flow through this reach was increased because of the reduction in floodplain and distributary conveyance. Based on these ISSDOT data, the increase in bed-load transport would be about 30 percent more than normal pool transport.

Sediment budget and GIS analyses. The St. Paul District has been measuring sediment and hydraulic parameters on the Mississippi River for many years. These District data were collected as part of habitat improvement projects and navigation channel maintenance activities. A sand budget was developed for Pools 1 through 10 using available information on sediment transport at U.S. Geological Survey gaging stations, long-term channel dredging data, studies of sediment deposition, and hydraulic data. Because of the small channel slope (because of the pooling effect created by the locks and dams) and the medium sand size, it appears that the majority of the bed-material transport occurs as sand

moving in sand waves. The St. Paul District also used GIS software to create bathymetry models of the main channel between River Mile 686 and River Mile 691 to determine the difference in bathymetry from one year to the next. The GIS computations do not seem to indicate large-scale or long-term changes in main channel bathymetry during the drawdown.

Transport function analysis. Analytic transport functions are another way to estimate bed-load transport in large sand-bed rivers. Many functions have been developed for a variety of river and flume conditions. The sediment and hydraulic analysis package Stable-channel Analytical Method (SAM), developed at ERDC, was used to run the transport functions selected for this project. Five functions were selected to compute bed load: Toffaleti, Meyer-Peter-Mueller, Schoklitsch, Einstein Bed-load, and Van Rijn bed-load.

Numerical analysis of effects of drawdown and wing dams on bed-load transport in Pool 8

Three sets of bed-load computational data were produced using the ISSDOT method, a sediment budget and GIS analysis, and analytic sediment transport functions. A numerical simulation model called ADaptive Hydraulics (ADH) was adapted and applied to the same study area. The purpose for this additional computational analysis was to determine if this numerical model could further corroborate previous conclusions regarding the effects of a drawdown and wing dam structures on bed load and navigation channel topography at the region of interest in Pool 8 on the upper Mississippi River. ADH was applied only in the hydrodynamic mode to ascertain river bottom stresses.

No tested and verified sediment routine for the upper Mississippi River was available in the ADH code at the time these numerical computations were being made. Instead, the shear stress produced on the bottom of the river was selected as an indicator of sediment mobilization. This shear stress value was computed for each nodal location of the computational mesh of Figure 20 for both survey trip 2 and survey trip 4 data. These values were then contoured to show their spatial distribution throughout the study area for both survey trips.

Effects of closure dams on navigation channel and back channel characteristics in Pool 13

Three closure dams were placed in Pool 13 of the river in April 2001. The river navigation channel and back channel characteristics were monitored for about 2.5 years after the placement of the closure dams. The monitoring consisted of measurements of the bathymetric and hydraulic changes that took place during this interval. The information assembled was used to evaluate the initial performance of the closure dam training structures.

Early in the planning stages of this project a concern was raised that the reduced flow in the back channel could induce sedimentation behind the islands and result in a loss of valuable over-wintering habitat for fish. There are several techniques that could be employed to measure the effectiveness of the closure dams, including bathymetric, hydraulic, and biological metrics. The purpose of the closure dams was to decrease sedimentation in the main channel without

causing significant sedimentation in the back channel. To test this, bathymetric and hydraulic surveys were conducted at various times after the construction of the closure dams. Changes observed during the monitoring time could then be used to determine whether or not the dams are performing as desired.

The study site was divided into two reaches. These reaches were the main channel just west of the islands, and the back channel just east of the islands. The main channel was further subdivided into three sections, and the back channel was subdivided into two sections. The locations were chosen because they represent the deepest water in each reach; these locations were also of prime interest during the planning and initiation of the study. The closure dams were constructed to increase the flow in the main channel so as to maintain or possibly increase the main channel depth without causing any deposition in the back channel. The effectiveness of the dams can best be evaluated by focusing the analysis on these five selected areas.

For each area in a given reach, a dense grid of bathymetric elevations was available. To determine if any overall change in bottom elevation in a given area occurred in the time between when any two data sets were taken, the entire data set was examined instead of examining elevation differences at specific isolated points. Some of the vertical changes in elevations are relatively small. The significance of the elevation changes was addressed by an analysis of variance (ANOVA) on the same data sets. Those results show that in all but two cases, the differences in the depth measurements, and thus the change in elevation, were statistically significant at the 95 percent confidence level.

Conclusions

Development of ISSDOT

Since it is physically impossible to actually measure total bed-load transport rates in large sand-bed rivers, other verification techniques must be used to determine the accuracy of the ISSDOT method for computing bed-load transport. There are at least two techniques for determining the accuracy of the ISSDOT method. The first is to compare ISSDOT results with mechanically measured data values on the same or similar rivers, taken at discrete locations and integrated across the entire river width. A second technique is to compare ISSDOT results with accepted analytic transport functions. Both techniques were applied.

For Pool 8 using the multi-beam data and the ISSDOT method, a value of 0.0041 kg/sec/m (0.003 lbs/sec/ft) of width was calculated. This is equivalent to about 148,780 kg/day (164 tons/day), or about 149 metric tons/day.

For the first technique, data taken on the Nile River in Egypt in 1991 using the Delft-Nile Sampler were used as a comparison for mechanically collected data because the hydraulic and sediment characteristics of the Nile River in the vicinity of the measurements were very close to those of Pool 8 on the upper Mississippi River. The result was 0.0175 kg/sec/m (0.0118 lb/sec/ft) of width. This is equivalent to about 635,030 kg/day (700 tons/day), or about 635 metric

tons/day. Thus, the measured value for the Nile River is about four times the ISSDOT computed value for Pool 8 on the upper Mississippi River.

Three analytical transport functions were selected and run using average channel parameters and the sediment characteristics of Pool 8. These functions were Einstein's bed-load function, Toffaleti's function, and van Rijn's function. These three transport functions computed 2,250,725 kg/day (2,481 tons/day), 312,070 kg/day (344 tons/day), and 1,684,640 kg/day (1,857 tons/day), respectively (2,255; 312; and 1,688 metric tons/day, respectively) of the bed-load portion of the bed-material load. The Toffaleti procedure produced results that were slightly more than twice the value computed using the ISSDOT method. The other two methods were substantially higher.

The ISSDOT methodology for determining bed-load transport slightly underpredicts transport when compared to both the mechanical bed sampling method and the analytical methods. This underprediction is related to the time-step interval between successive bathymetric measurements. Future surveys should be at shorter and more regularly spaced time intervals. Ultimately, large-scale proof-of-concept laboratory flume studies should be conducted.

Effects of drawdown and wing dams on bed-load transport in Pool 8

For the same set of hydraulic and sediment characteristics, both the ISSDOT method of computing bed-load transport gradient and the analytic transport functions computed transport gradients/rates between 36,285 and 725,745 kg/day (40 and 800 ton/day, respectively) through the study reach. In each method the lower values corresponded to the normal pool condition, and the higher transport values corresponded to the drawdown conditions. Supporting these data, the sand budget analysis provided an estimate of a mean daily transport rate of bed load between 249,475 and 498,950 kg/day (275 and 550 ton/day, respectively). The transport rates for this case depend on the amount of bed material that can be proven to be in suspension.

Three sets of bed-load transport measurement data have been presented, and all are within an order of magnitude of each other. These data suggest the following: (a) The observed drawdown did indeed have the effect of increasing sediment mobilization within the study reach. (b) The original wing dam structures as designed, and in conjunction with a drawdown, positively influence sediment movement in the reach. (c) It will be possible to project sediment movement before, during, and after such drawdown events.

By utilizing ISSDOT technology and other river management information gleaned from this monitoring study, river managers could more efficiently plan their dredging requirements for events such as the Pool 8 drawdown.

Numerical analysis of effects of drawdown and wing dams on bed-load transport in Pool 8

The two-dimensional hydrodynamic numerical model ADaptive Hydraulics (ADH) provides more detail than the other analytic techniques used in this study. Though this numerical simulation model requires more time, effort, and data for

execution than the other techniques, it is well worth the extra effort when detailed temporal and/or spatial information is required in a given study reach such as Pool 8. The high-resolution bathymetric data obtained here allowed for a very detail mapping of the river bottom and, thus, an excellent representation of bottom elevations in the numerical mesh by ADH. Conclusions previously reached by different methodologies were substantiated and refined. ADH showed that the wing dam structures in combination with a water level drawdown did indeed positively influence sediment movement in the study reach of interest of Pool 8 on the upper Mississippi River.

Effects of closure dams on navigation channel and back channel characteristics in Pool 13

This MCNP monitoring investigation has provided a quantitative measure of the bathymetric changes in the study area of interest of Pool 13 on the upper Mississippi River after the closure dam training structures were installed. This successful study has been possible through careful analysis of high-resolution bathymetric surveys. The data show spatial and temporal scour and deposition trends in the study area and also address the statistical significance of each.

Main channel. For the main channel, Area 1 and Area 2 showed a scour trend between November 2001 and June 2002. From June 2002 to July 2004, both areas showed a deposition trend. Thus, short-term occurrences of scour and then redeposition were measurable and statistically significant at the 95 percent confidence interval. However, over the entire monitoring period of November 2001 to July 2004, the net result showed no discernable change in the main channel bathymetry with regard to average depths in Area 1 and Area 2.

Area 3 of the main channel showed the same trend of scour and then deposition as Area 1 and Area 2 for the same time periods. However, over the entire monitoring period, the net result was a discernable scour trend.

For the main channel, it can be concluded that Area 1, Area 2, and Area 3 all had the same trend of scour first and then redeposition. The only difference between them was that in Area 3 the redeposition was not as much and, thus, still showed a measurable difference (slight scour) between the first and last surveys. Whether the redeposition trend will continue in all three areas cannot be determined from these data.

Back channel. For the back channel Area 1, there was only one "difference" data set. It showed a net deposition trend of nearly 0.15 m (0.5 ft) in that area between June 2002 and July 2004. In Area 2 of the back channel, all measurements show a net deposition trend, with the maximum being about 0.34 m (1.1 ft) over the entire survey period of 32 months. The net deposition in the back channel is statistically significant at the 95 percent confidence interval. As in the main channel, whether the deposition in the back channel will continue cannot be determined from these data.

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Appendix A
Analysis of Variance, Elevation Data Points from Multi-beam Survey, Pool 13, Upper Mississippi River

Examination of all river-bottom elevation data points from the entire area of interest in Pool 13 yields meaningful quantitative knowledge. To assist in visualizing the many thousand data points in a single survey, the data were plotted as percentile curves. However, since changes in elevation may be quite small and difficult to discern, an Analysis of Variance technique was performed on the data points to ascertain significance of the elevation changes.

Null Hypotheses

The differences in depth measurements between the two grids are not statistically significant; i.e., there exist no statistically discernable changes in the elevation measurements between the two trips.

Back Channel Study, Area 1
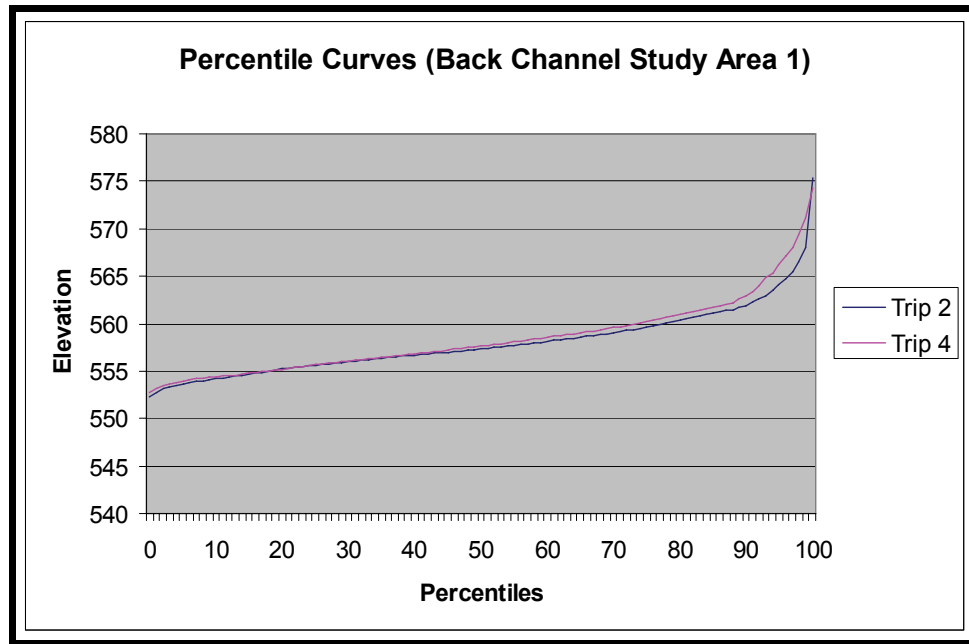
Percentile Curves (Back Channel Study Area 1)

Survey Trip 2 (June 2002) versus Survey Trip 4 (July 2004)

Survey trip 2 number of data points = 5,178. Survey trip 4 number of data points = 5,178.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	561.50739	561.50739	45.21696
Error	10,354	128,576.6993	12.41807024	
Total	10,355	129,138.2067		

Since the value obtained for $F_{calculated}$ = 45.21696 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 10,354) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.

Appendix A   Analysis of Variance, Elevation Data Points from Multi-beam Survey

Back Channel Study, Area 2

Percentile Curves (Back Channel Study Area 2)

Survey Trip 1 (November 2001) versus Survey Trip 2 (June 2002)

Survey trip 1 number of data points = 25,754. Survey trip 2 number of data points = 25,754.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	1,599.034807	1,599.034807	56.19611
Error	51,506	1,465,579.867	28.4545464	
Total	51,507	1,467,178.902		

Since the value obtained for $F_{calculated}$ = 56.19611 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 51,506) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.
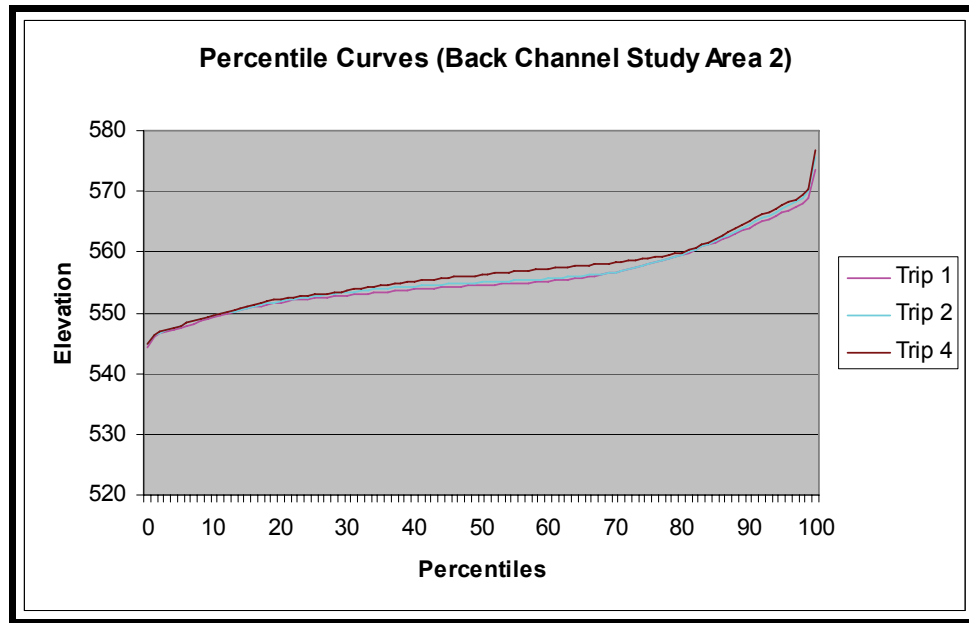
Survey Trip 2 (June 2002) versus Survey Trip 4 (July 2004)

Survey trip 2 number of data points = 25,754. Survey trip 4 number of data points = 25,754.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	6,483.438375	6,483.438375	218.5742
Error	51,506	1,527,792.597	29.66241986	
Total	51,507	1,534,276.036		

Since the value obtained for $F_{calculated}$ = 218.5742 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 51,506) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.
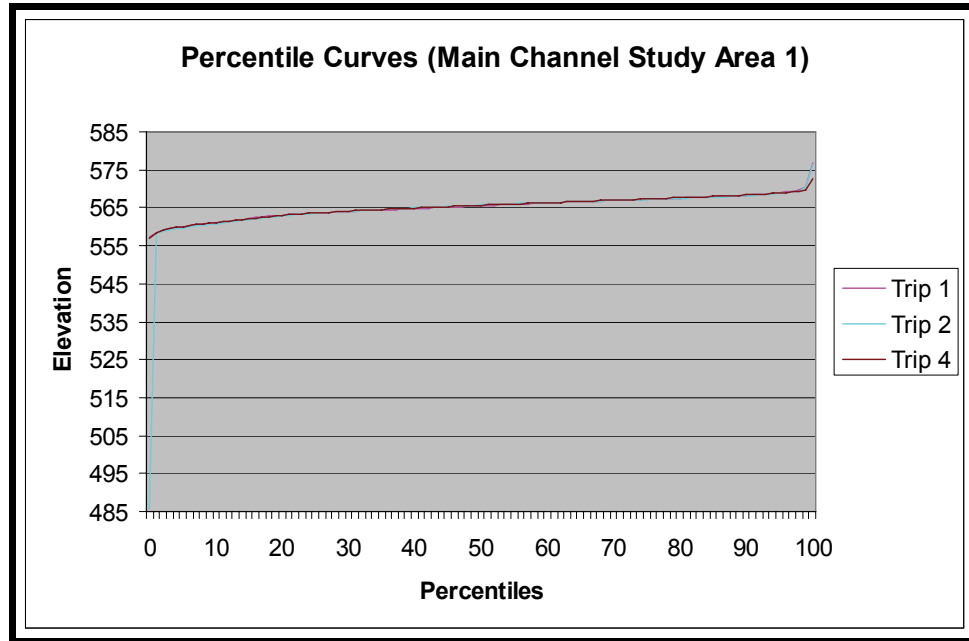
Survey Trip 1 (November 2001) versus Survey Trip 4 (July 2004)

Survey trip 1 number of data points = 25,754. Survey trip 4 number of data points = 25,754.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	14,522.11406	14,522.11406	498.865
Error	51,506	1,499,355.555	29.11030861	
Total	51,507	1,513,877.669		

Since the value obtained for $F_{calculated}$ = 498.865 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 51,506) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.

Main Channel Study, Area 1

Percentile Curves (Main Channel Study Area 1)

Survey Trip 1 (November 2001) versus Survey Trip 2 (June 2002)

Survey trip 1 number of data points = 64,154. Survey trip 2 number of data points = 64,154.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	138.2764282	138.2764282	17.65318
Error	128,306	1,005,013.921	7.832945625	
Total	128,307	1,005,152.198		

Since the value obtained for $F_{calculated}$ = 17.65318 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 128,306) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.

Survey Trip 2 (June 2002) versus Survey Trip 4 (July 2004)

Survey trip 2 number of data points = 64,154. Survey trip 4 number of data points = 64,154.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	254.5379791	254.5379791	33.29497
Error	128,306	980,891.4432	7.64493822	
Total	128,307	981,145.9812		

Since the value obtained for $F_{calculated}$ = 33.29497 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 128,306) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.
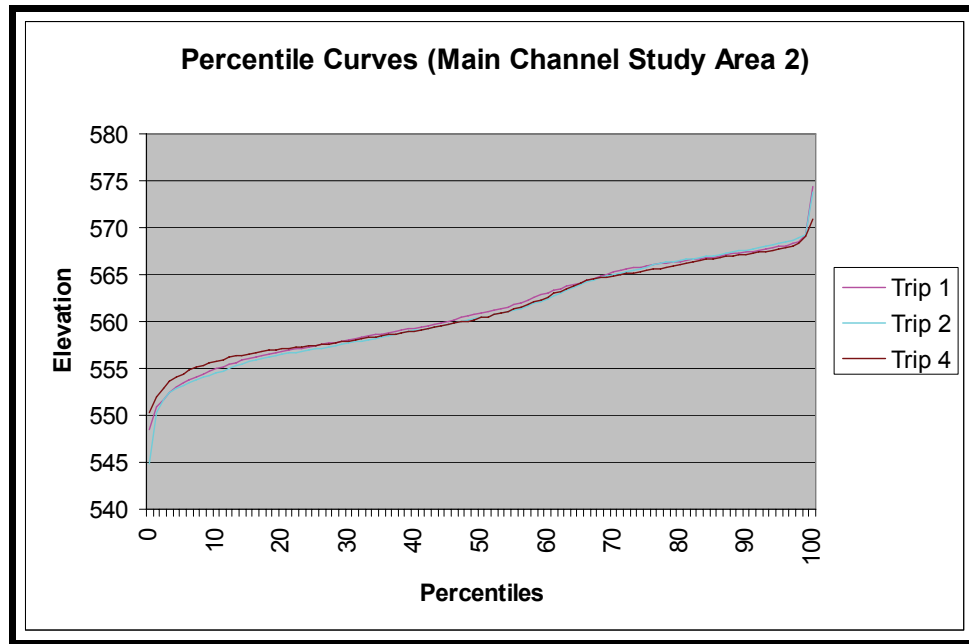
Survey Trip 1 (November 2001) versus Survey Trip 4 (July 2004)

Survey trip 1 number of data points = 64,154. Survey trip 4 number of data points = 64,154.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	17.59925079	17.59925079	2.389591
Error	128,306	944,968.8891	7.364962582	
Total	128,307	944,986.4883		

Since the value obtained for $F_{calculated}$ = 2.389591 **does not exceed** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 128,306) degrees of freedom, the null hypothesis cannot be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are not statistically significant**.

Main Channel Study, Area 2

Percentile Curves (Main Channel Study Area 2)

Survey Trip 1 (November 2001) versus Survey Trip 2 (June 2002)

Survey trip 1 number of data points = 18,467. Survey trip 2 number of data points = 18,467.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	498.7702847	498.7702847	20.76356
Error	36,932	887,159.3398	24.02142694	
Total	36,933	887,658.1101		

Since the value obtained for $F_{calculated}$ = 20.76356 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 36,932) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.

Survey Trip 2 (June 2002) versus Survey Trip 4 (July 2004)

Survey trip 2 number of data points = 18,467. Survey trip 4 number of data points = 18,467.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	299.3317432	299.3317432	13.35219
Error	36,932	827,947.9785	22.41817336	
Total	36,933	828,247.3102		

Since the value obtained for $F_{calculated}$ = 13.35219 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 36,932) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance; we conclude that the differences in the depth measurements for the two trips **are statistically significant**.
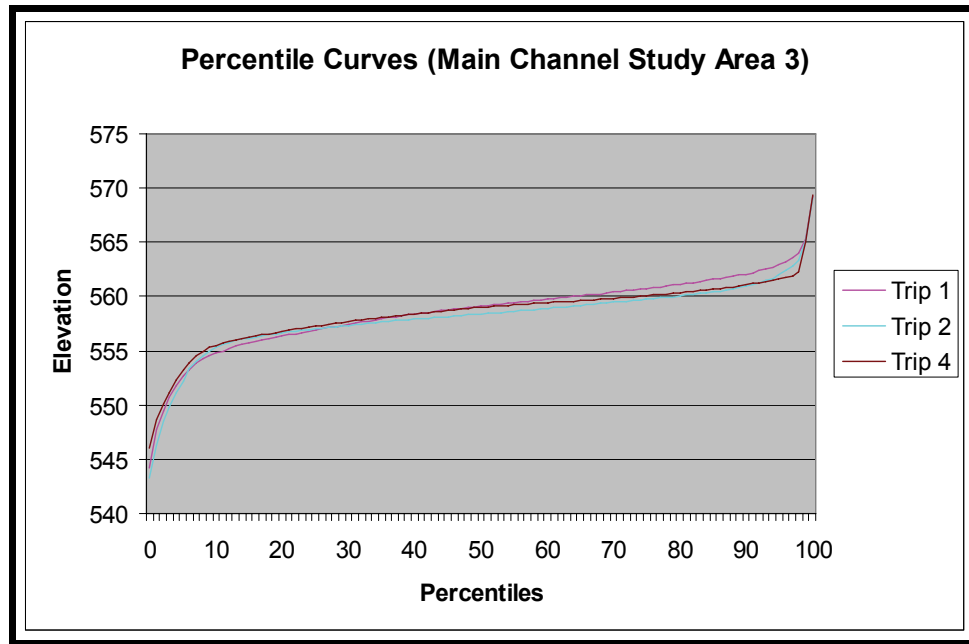
Survey Trip 1 (November 2001) versus Survey Trip 4 (July 2004)

Survey trip 1 number of data points = 18,467. Survey trip 4 number of data points = 18,467.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	25.32061005	25.32061005	1.171158
Error	36,932	798,475.618	21.62015645	
Total	36,933	798,500.9387		

Since the value obtained for $F_{calculated}$ = 1.171158 **does not exceed** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 36,932) degrees of freedom, the null hypothesis cannot be rejected at the 0.05 level of significance; we conclude that the differences in the depth measurements for the two trips **are not statistically significant**.

Main Channel Study, Area 3

Percentile Curves (Main Channel Study Area 3)

Survey Trip 1 (November 2001) versus Survey Trip 2 (June 2002)

Survey trip 1 number of data points = 31,869. Survey trip 2 number of data points = 31,869.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	4.577.829132	4.577.829132	459.6652
Error	63.736	634.750.1046	9.959051471	
Total	63.737	639.327.9337		

Since the value obtained for $F_{calculated}$ = 459.6652 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 63.736) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance; we conclude that the difference in the depth measurements for the two trips **are statistically significant**.

Survey Trip 2 (June 2002) versus Survey Trip 4 (July 2004)

Survey trip 2 number of data points = 31,869. Survey trip 4 number of data points = 31,869.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	2,182.326691	2,182.326691	260.0835
Error	63,736	534,800.4594	8.390869515	
Total	63,737	536,982.7861		

Since the value obtained for $F_{calculated}$ = 260.0835 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 63736) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.

Survey Trip 1 (November 2001) versus Survey Trip 4 (July 2004)

Survey trip 1 number of data points = 31,869. Survey trip 4 number of data points = 31,869.

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F
Trips	1	438.662735	438.662735	48.24798
Error	63,736	579,477.2385	9.091835674	
Total	63,737	579,915.9013		

Since the value obtained for $F_{calculated}$ = 48.24798 **exceeds** $F_{tabulated}$ = 3.84, the value of $F_{0.05}$ with 1 and infinite (approximating the actual value 63,736) degrees of freedom, the null hypothesis can be rejected at the 0.05 level of significance. It is concluded that the differences in the depth measurements for the two trips **are statistically significant**.

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Effects of Pool Drawdown and Wing Dams (Pool 8), and Closure Dams (Pool 13), on Navigation Channel Sedimentation Processes, Upper Mississippi River

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

Construction of navigation locks and dams on the upper Mississippi River about 60 years ago submerged wing dam training structures, thereby reducing their effectiveness and increasing secondary channel and floodplain conveyance. The U.S. Army Engineer District, St. Paul, executed a drawdown of Pool 8 (upstream of Lock and Dam No. 8) near La Crosse, WI, during the summers of 2001 and 2002. Water levels were allowed to drop below normal minimum values to expose mud flats, promote seed germination, and benefit fish and wildlife. By lowering water levels during a drawdown, wing dam training structures submergence and floodplain conveyance will be decreased, and flow patterns around the training structures will be altered. This could result in sediment mobilization and scour in the navigation channel.

During the spring of 2001, three closure dams were constructed in Pool 13 (upstream of Lock and Dam No.13) by the U.S. Army Engineer District, Rock Island, near Savannah, IL. These closure dams are actually submerged weirs that should allow water to continue to flow into the backwater areas of the islands of Pool 13, but at reduced rates. At issue is whether the main channel might require reduced dredging in future years as a result of the construction of the closure dams and, also, whether the backwaters of the eastern side of the islands will fill with sediment.

(Continued)

15. SUBJECT TERMS

Closure dams	Sedimentation
Drawdown	Upper Mississippi River
	Wing dams

16. SECURITY CLASSIFICATION OF:

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14. ABSTRACT (Concluded)

A new and expedient methodology for the computation of bed-load transport (Integrated Section Surface Difference Over Time (ISSDOT)) was developed using multi-beam bathymetric data. The total river bed volume change with time, when multiplied by the density of the water/sediment mixture, yields a mass transport rate. Results of ISSDOT computations for Pool 8, and other analyses (sediment budget and geographic information system (GIS) analyses, and transport function analysis) of the same river region, confirm that: (a) the observed drawdown did indeed have the effect of increasing sediment mobilization within the study reach, (b) the original wing dam structures as designed, and in conjunction with a drawdown, positively influence sediment movement in the reach, and (c) it will be possible to project sediment movement before, during, and after such drawdown events. By utilizing ISSDOT technology and other river management information gleaned from this monitoring study, river managers can more efficiently plan their dredging requirements for events such as the Pool 8 drawdown.

For the region of interest at Pool 13, in the main channel, two areas showed short-term occurrences of scour and then re-deposition that was measurable and statistically significant. However, over the entire monitoring period of November 2001 to July 2004, the net result showed no discernable change in the main channel bathymetry with regard to average depths in these two areas. A third area of the main channel showed the same scour and then deposition trend as the other two areas for the same time periods. However, over the entire monitoring period, the net result was a discernable scour trend in the main channel. For the back channel, one area showed a net deposition trend of nearly 0.15 m (0.5 ft) in that area between June 2002 and July 2004. In another area of the back channel, all measurements showed a net deposition trend with the maximum being about 0.34 m (1.1 ft) over the entire survey period of 32 months. The net deposition in the back channel is statistically significant. As in the main channel, whether the deposition in the back channel will continue cannot be determined from the present data.